US011743659B2

(12) **United States Patent**
Liang et al.

(10) **Patent No.: US 11,743,659 B2**
(45) **Date of Patent: *Aug. 29, 2023**

(54) **AIR-PULSE GENERATING DEVICE AND SOUND PRODUCING METHOD THEREOF**

(71) Applicant: **xMEMS Labs, Inc.**, Santa Clara, CA (US)

(72) Inventors: **Jemm Yue Liang**, Sunnyvale, CA (US); **Wen-Chien Chen**, New Taipei (TW); **Jye Ren**, Taipei (TW)

(73) Assignee: **xMEMS Labs, Inc.**, Santa Clara, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **17/553,808**

(22) Filed: **Dec. 17, 2021**

(65) **Prior Publication Data**

US 2022/0225032 A1 Jul. 14, 2022

Related U.S. Application Data

(60) Provisional application No. 63/171,281, filed on Apr. 6, 2021, provisional application No. 63/143,510, filed

(Continued)

(51) **Int. Cl.**

H04R 23/00	(2006.01)
H04R 7/04	(2006.01)

(52) **U.S. Cl.**
CPC ***H04R 23/00*** (2013.01); ***H04R 7/04*** (2013.01); *H04R 2440/07* (2013.01)

(58) **Field of Classification Search**
CPC H04R 23/00; H04R 23/004; H04R 1/028; H04R 1/42; H04R 9/022; H04R 7/04;

(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,646,733	A	3/1987	Stroh
4,942,939	A	7/1990	Harrison

(Continued)

FOREIGN PATENT DOCUMENTS

JP	2022-160366	A	10/2022
JP	2022-160367	A	10/2022

(Continued)

OTHER PUBLICATIONS

Liang, the specification, including the claims, and drawings in the U.S. Appl. No. 17/553,806, filed Dec. 17, 2021.

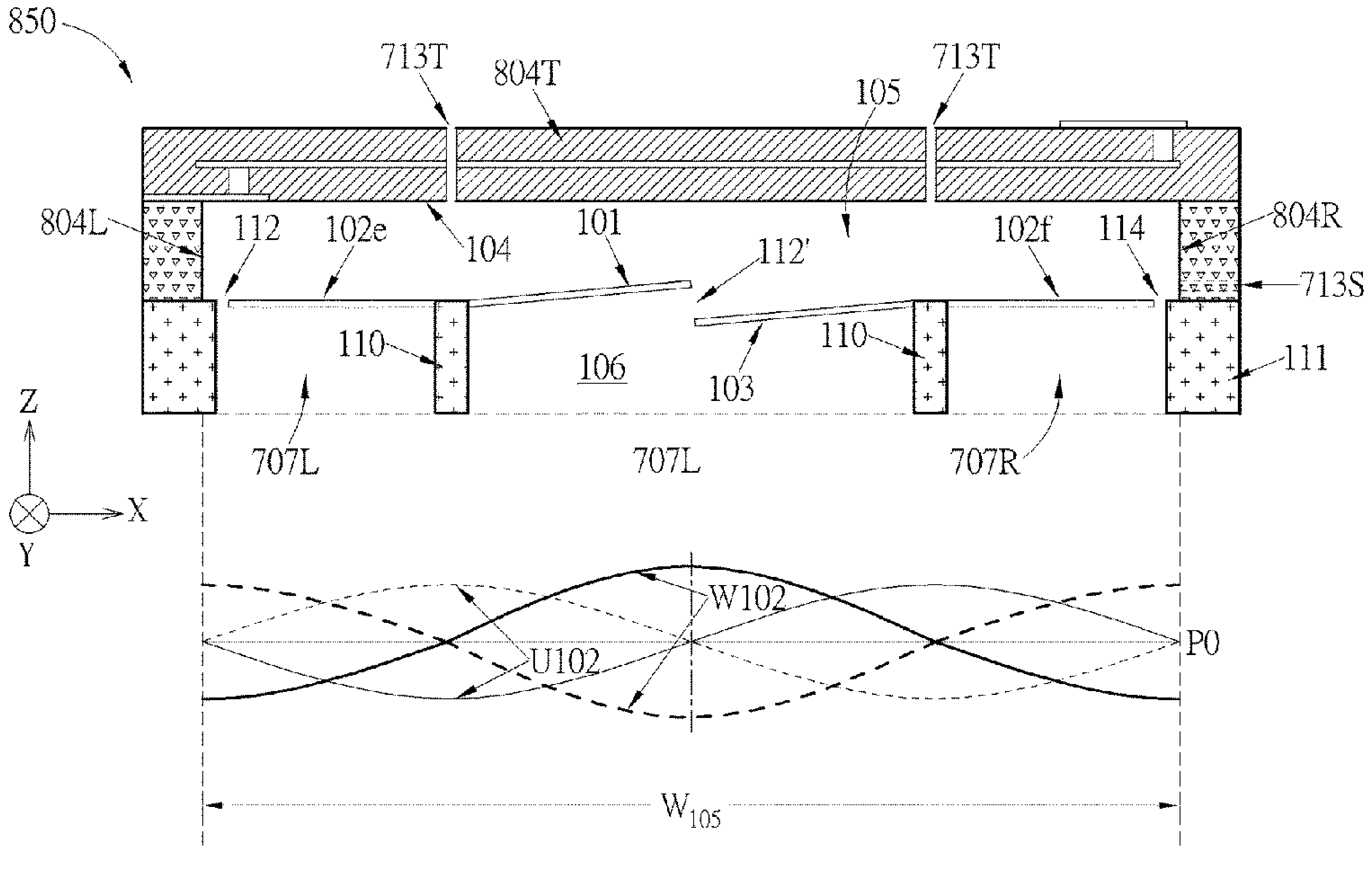
(Continued)

Primary Examiner — Carolyn R Edwards
Assistant Examiner — Julie X Dang
(74) *Attorney, Agent, or Firm* — Winston Hsu

(57) **ABSTRACT**

An air-pulse generating device includes a membrane structure, a valve structure, and a cover structure. A chamber is formed between the membrane structure, the valve structure and the cover structure. An air wave vibrating at an operating frequency is formed within the chamber. The valve structure is configured to be actuated to perform an open-and-close movement to form at least one opening. The at least one opening connects air inside the chamber with air outside the chamber. The open-and-close movement is synchronous with the operating frequency.

24 Claims, 15 Drawing Sheets



Related U.S. Application Data

on Jan. 29, 2021, provisional application No. 63/142,627, filed on Jan. 28, 2021, provisional application No. 63/139,188, filed on Jan. 19, 2021, provisional application No. 63/138,449, filed on Jan. 17, 2021, provisional application No. 63/137,479, filed on Jan. 14, 2021.

(58) **Field of Classification Search**

CPC H04R 2440/07; H04R 19/02; H04R 1/403; H04R 1/2811; H04R 1/24; H04R 3/04; H04R 2201/003; H04R 19/005; H04R 1/025; H04R 1/28; H04R 1/2823; H04R 7/08; H04R 2217/03; H04R 2499/11; G10K 11/002; G10K 11/26; G10K 5/02; H04W 4/14

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,109,948	A	5/1992	Sandstrom	
5,611,406	A	3/1997	Matsuzaki	
7,736,324	B1	6/2010	Helgeson	
10,425,732	B1 *	9/2019	Liang	H04R 3/04
10,484,784	B1	11/2019	Liang	
2004/0024455	A1	2/2004	de Vries	
2005/0235988	A1	10/2005	Hansen	
2008/0121220	A1	5/2008	Wilder	
2012/0018244	A1	1/2012	Robert	
2012/0032892	A1 *	2/2012	Pasquero	G06F 3/016 345/173
2012/0081337	A1	4/2012	Camp, Jr.	
2013/0279738	A1	10/2013	Daley	
2014/0064036	A1	3/2014	Tseng	
2014/0084396	A1	3/2014	Jenkins	
2014/0341394	A1	11/2014	Croft, III	
2016/0059206	A1 *	3/2016	Chen	G01N 1/4077 422/127
2016/0366521	A1	12/2016	Pinkerton, III	
2017/0041708	A1 *	2/2017	Barzen	H04R 29/001
2017/0201192	A1 *	7/2017	Tumpold	H02N 1/006
2018/0179048	A1	6/2018	Schenk	
2019/0020944	A1	1/2019	Kubo	
2019/0116417	A1	4/2019	Liang	
2019/0238974	A1 *	8/2019	Hong	H04R 3/04
2019/0313189	A1	10/2019	Liang	
2020/0059719	A1	2/2020	Liang	
2022/0047841	A1	2/2022	Duraán Vargas	

FOREIGN PATENT DOCUMENTS

JP	2022-160368	A	10/2022
KR	10-1901204	B1	9/2018
KR	10-2019-0043489	A	4/2019
KR	10-2019-0116898	A	10/2019
KR	10-2093804	B1	3/2020
WO	2016/202790	A2	12/2016

OTHER PUBLICATIONS

Liang, the specification, including the claims, and drawings in the U.S. Appl. No. 17/553,813, filed Dec. 17, 2021.

* cited by examiner

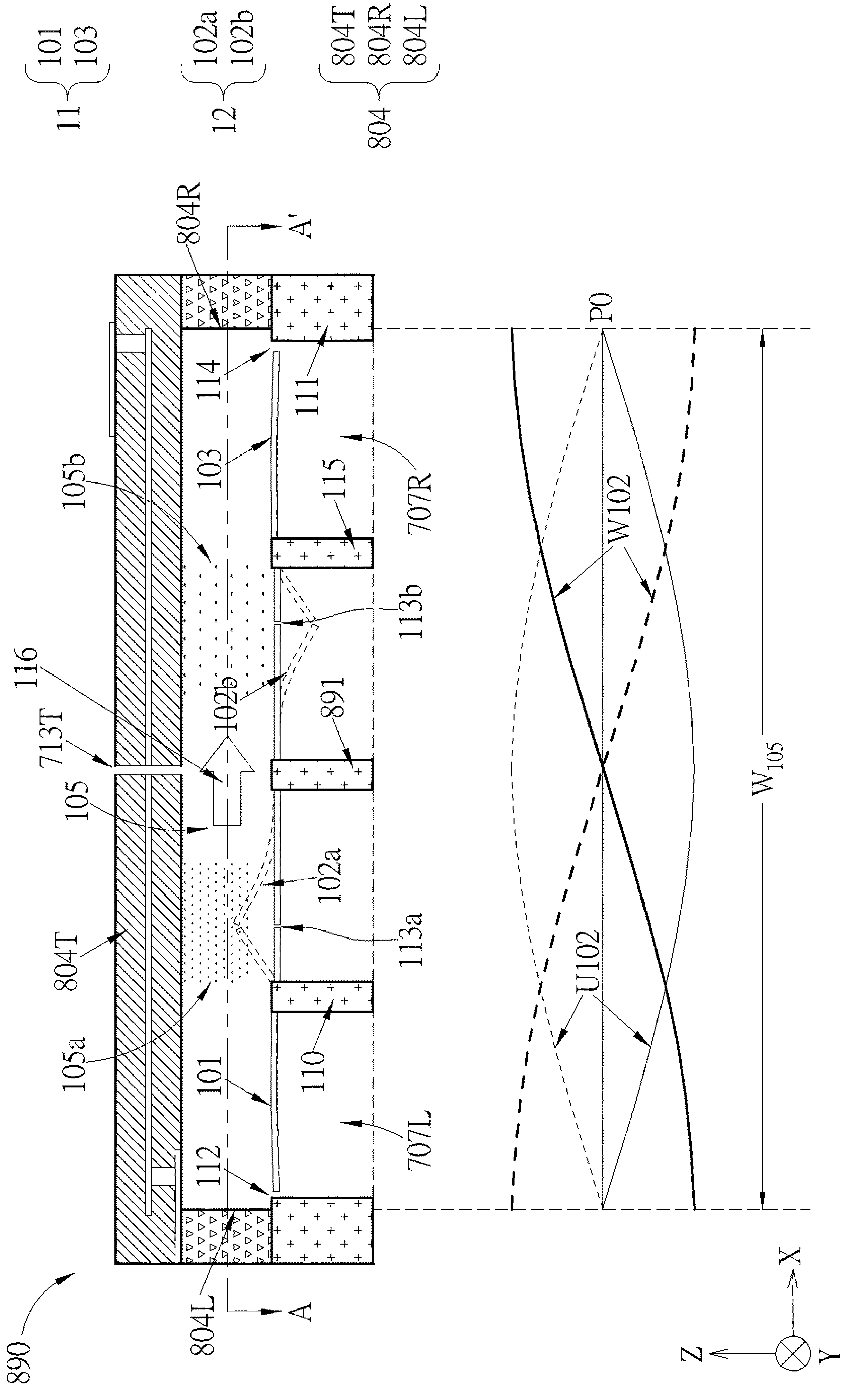
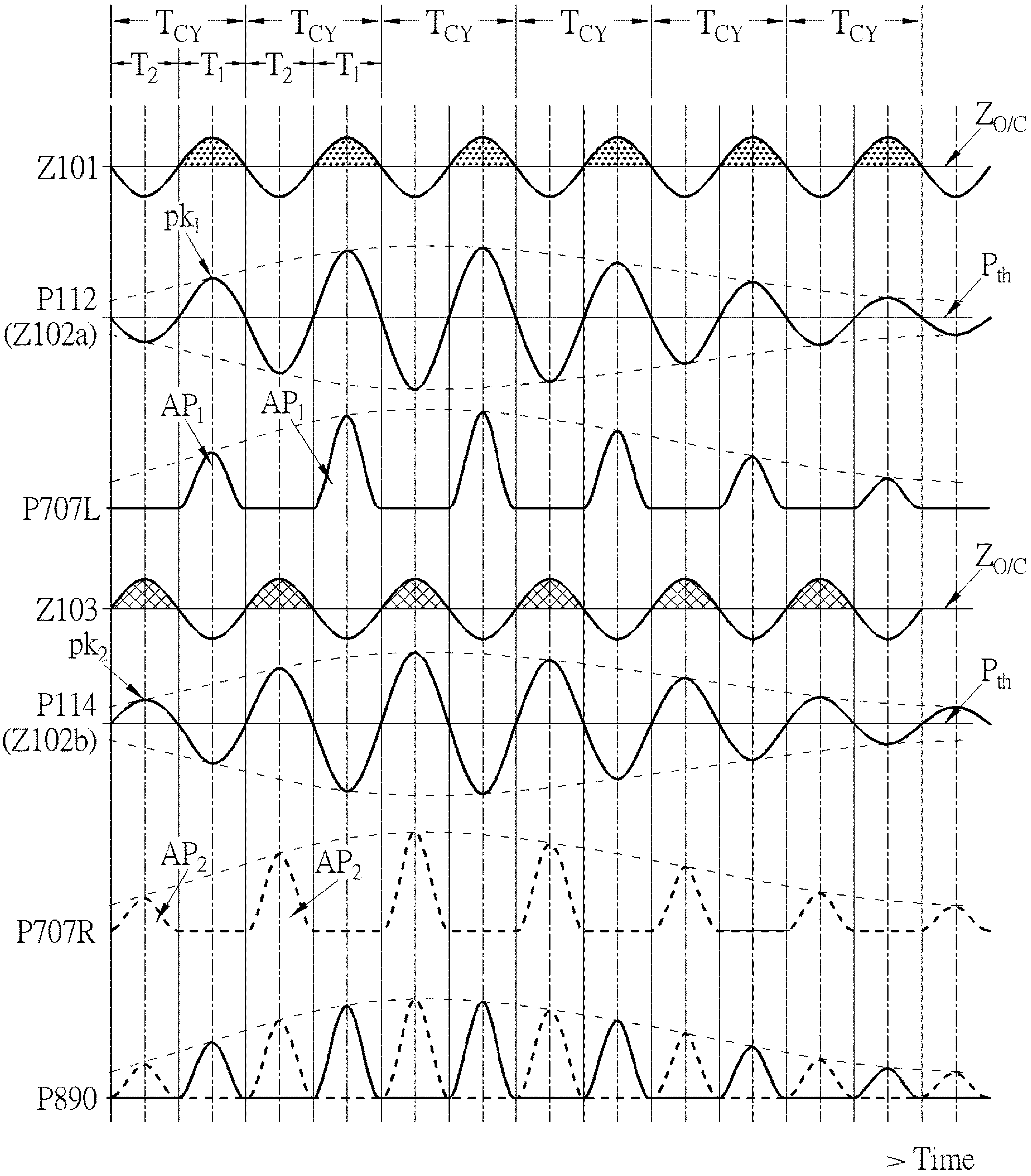

11
101
103
12
102a
102b
804
804T
804R
804L
890
804L
A
804R
A'
804T
105a
105
713T
116
105b
101
112
110
102a
113a
891
102b
113b
115
103
114
111
707L
707R
P0
W102
U102
W105
X
Y
Z

FIG. 1



T_{CY}
T_2
T_1
Z101
$Z_{O/C}$
pk_1
P112
(Z102a)
P_{th}
AP_1
P707L
Z103
pk_2
P114
(Z102b)
AP_2
P707R
P890
Time

FIG. 2

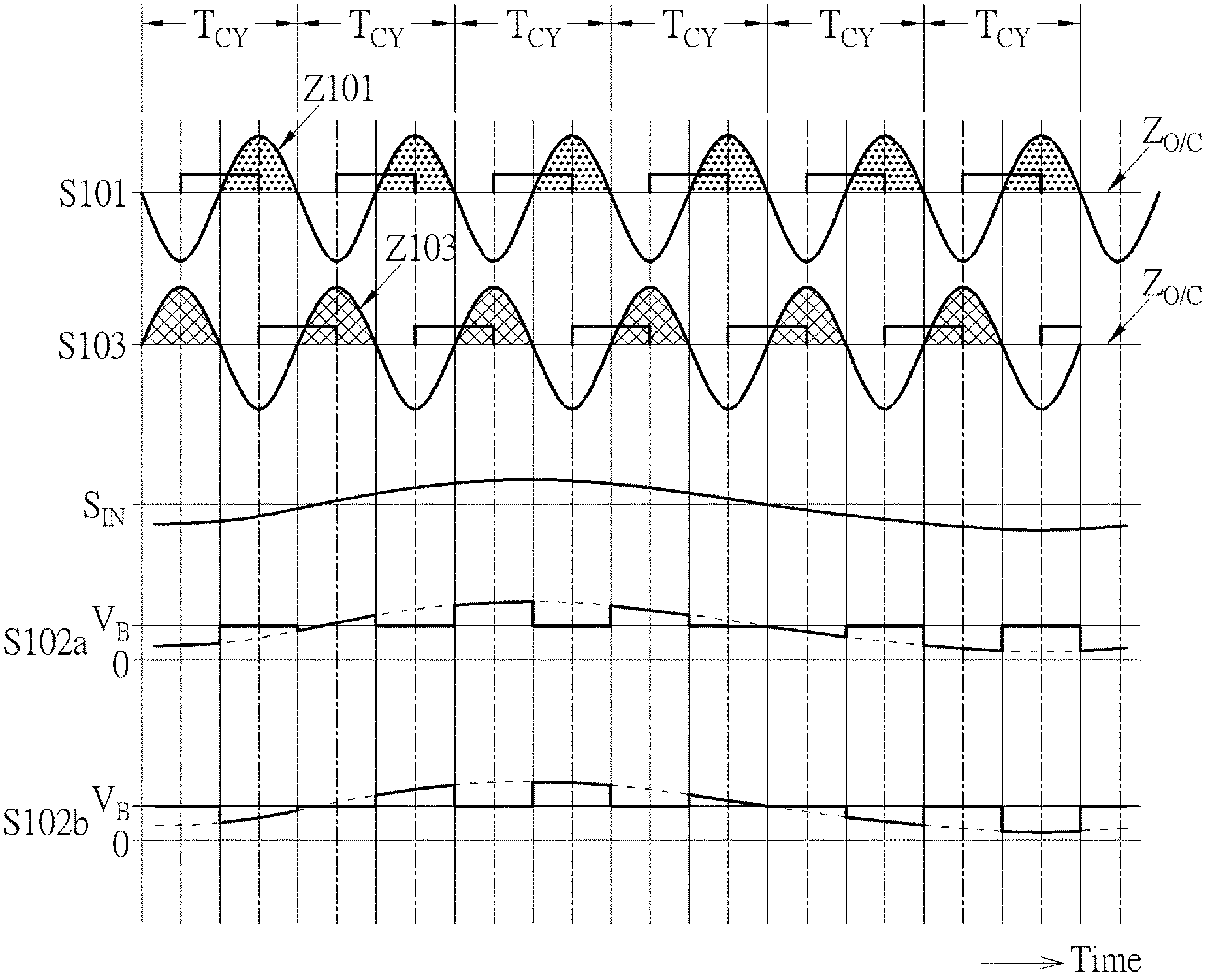

T_{CY}
T_{CY}
T_{CY}
T_{CY}
T_{CY}
T_{CY}
Z101
$Z_{O/C}$
S101
Z103
$Z_{O/C}$
S103
S_{IN}
S102a
V_B
0
S102b
V_B
0
Time

FIG. 3

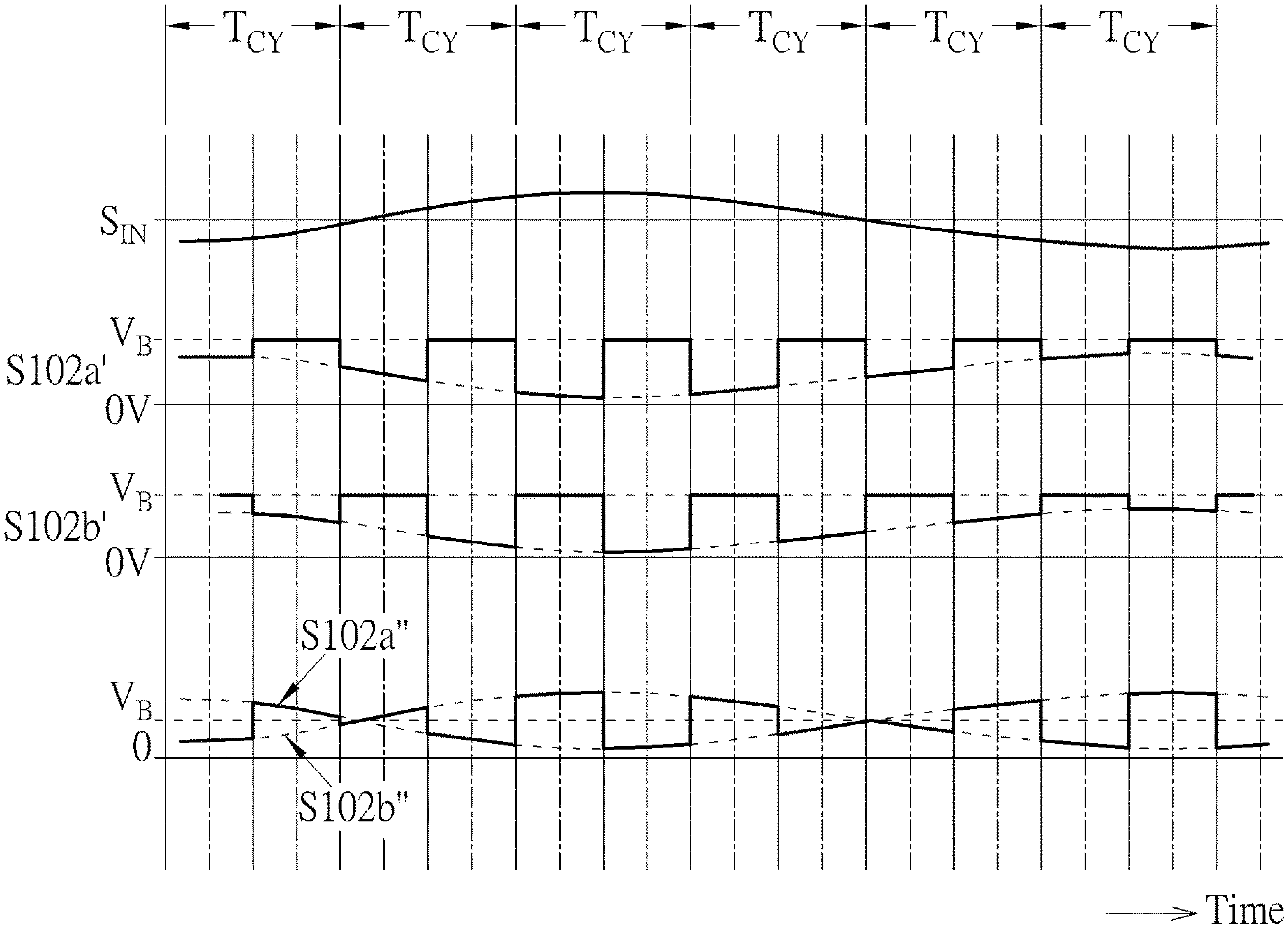

T_{CY}
T_{CY}
T_{CY}
T_{CY}
T_{CY}
T_{CY}
S_{IN}
V_B
S102a'
0V
V_B
S102b'
0V
S102a"
V_B
0
S102b"
Time

FIG. 4

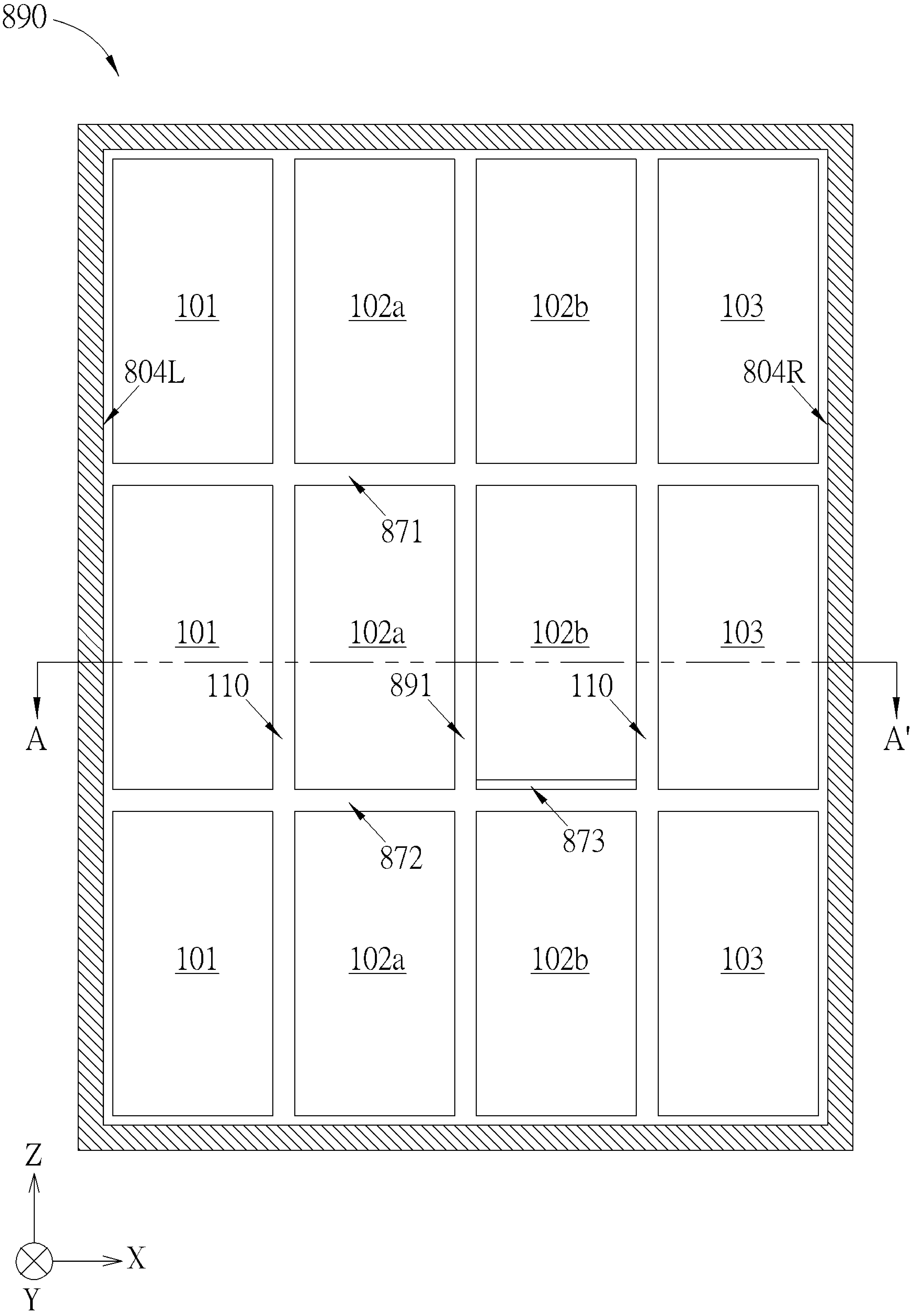

890
101
102a
102b
103
804L
804R
871
101
102a
102b
103
A
110
891
110
A'
872
873
101
102a
102b
103
Z
X
Y

FIG. 5

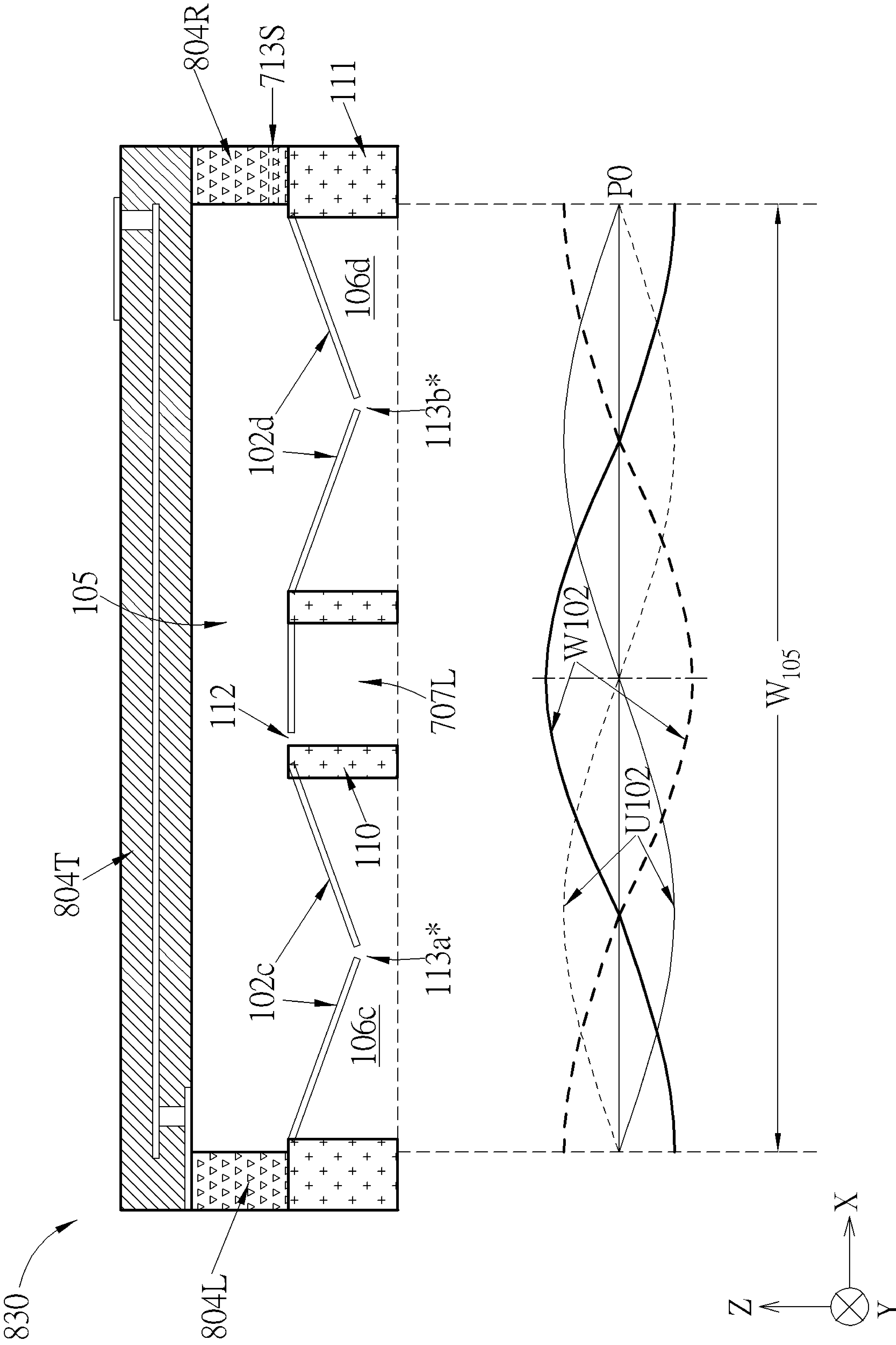

804R
713S
111
P0
106d
102d
113b*
105
W102
W105
707L
112
110
U102
804T
102c
113a*
106c
830
804L
X
Z
Y

FIG. 6

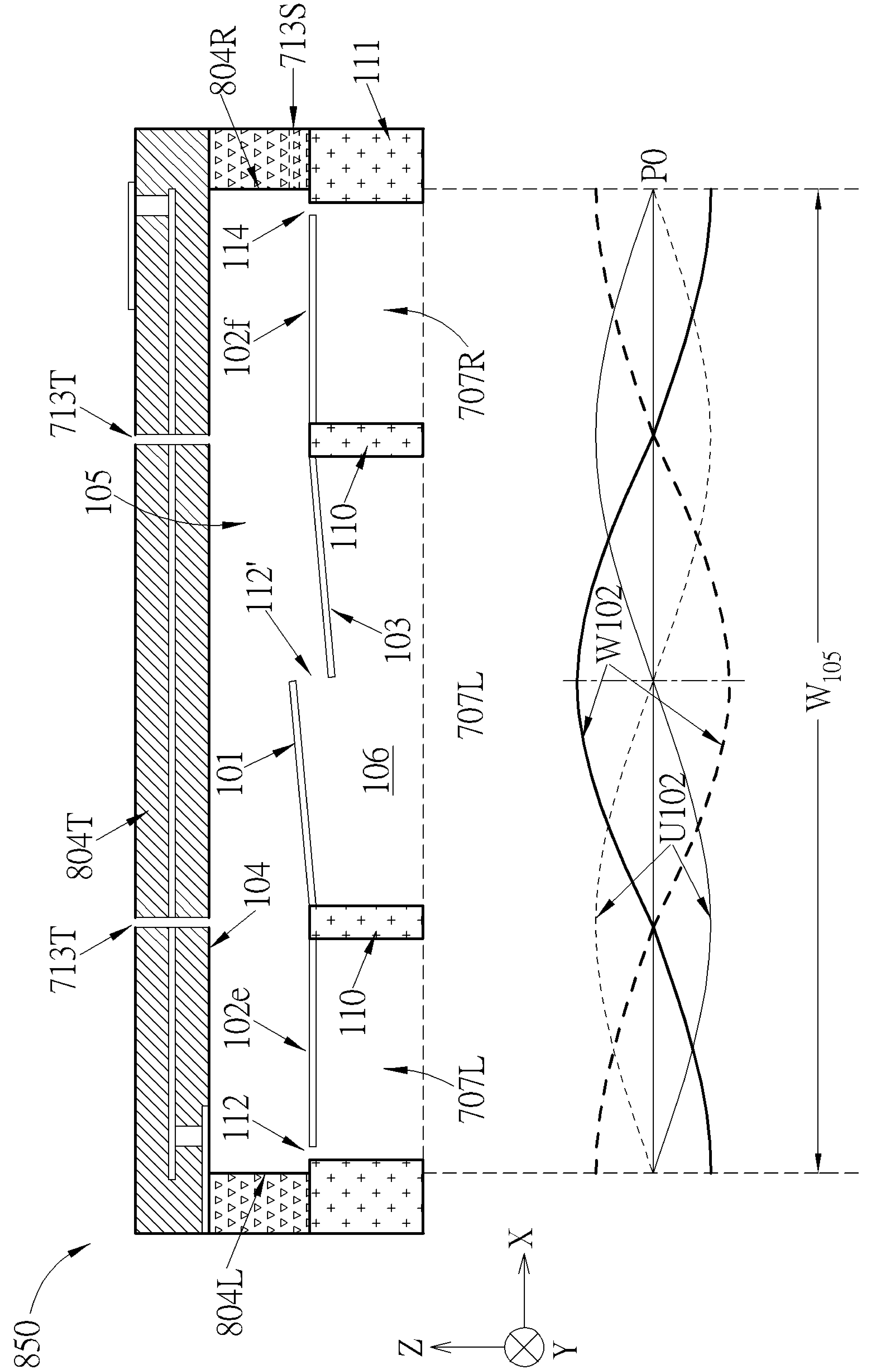

850
804L
804R
713S
111
P0
114
102f
707R
713T
105
110
112'
103
W102
707L
101
106
804T
U102
104
713T
102e
110
707L
112
W_{105}
X
Z
Y

FIG. 7

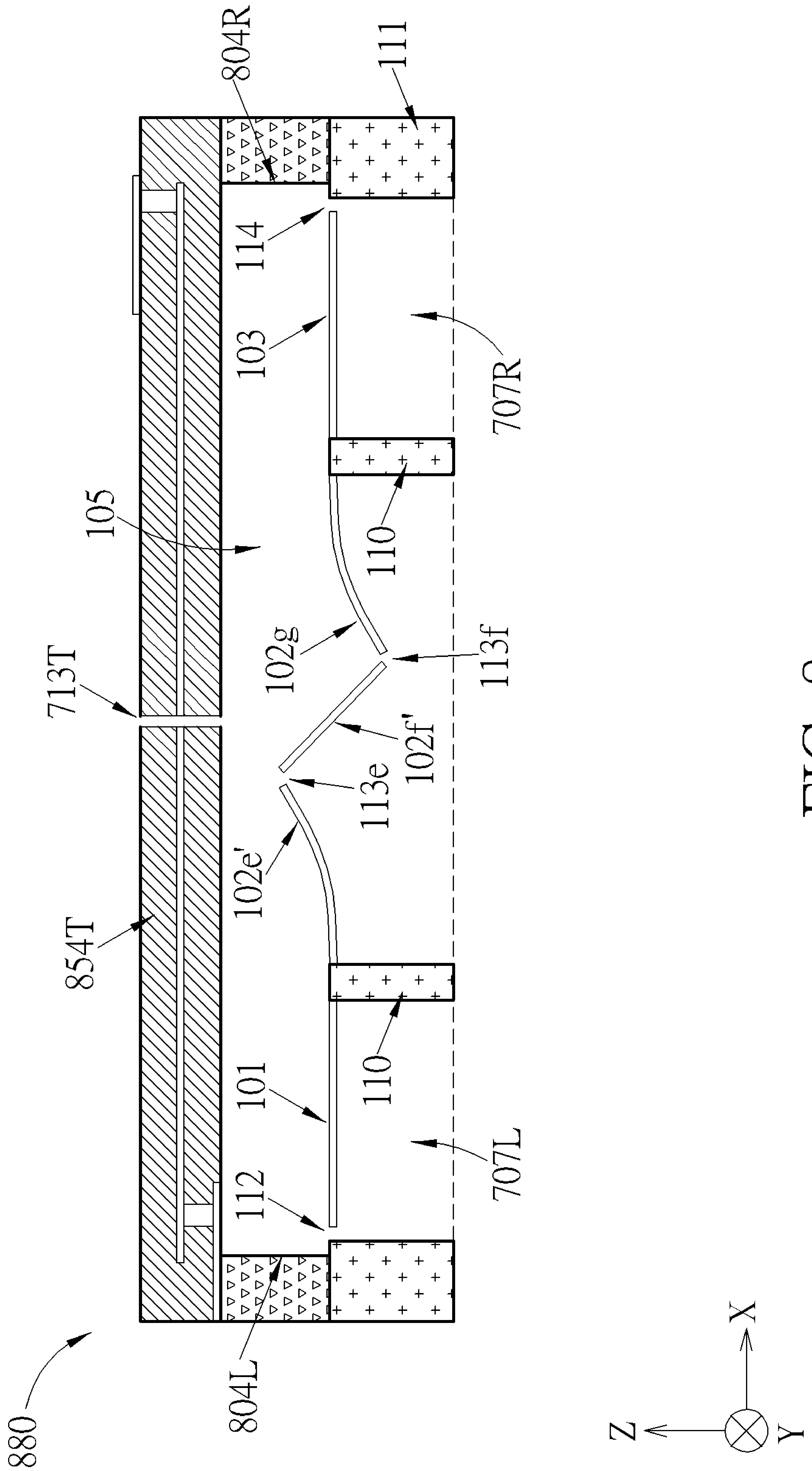

880
804L
854T
713T
105
804R
112
101
102e'
102g
114
103
110
113e
102f'
113f
110
707L
707R
111
X
Y
Z

FIG. 8

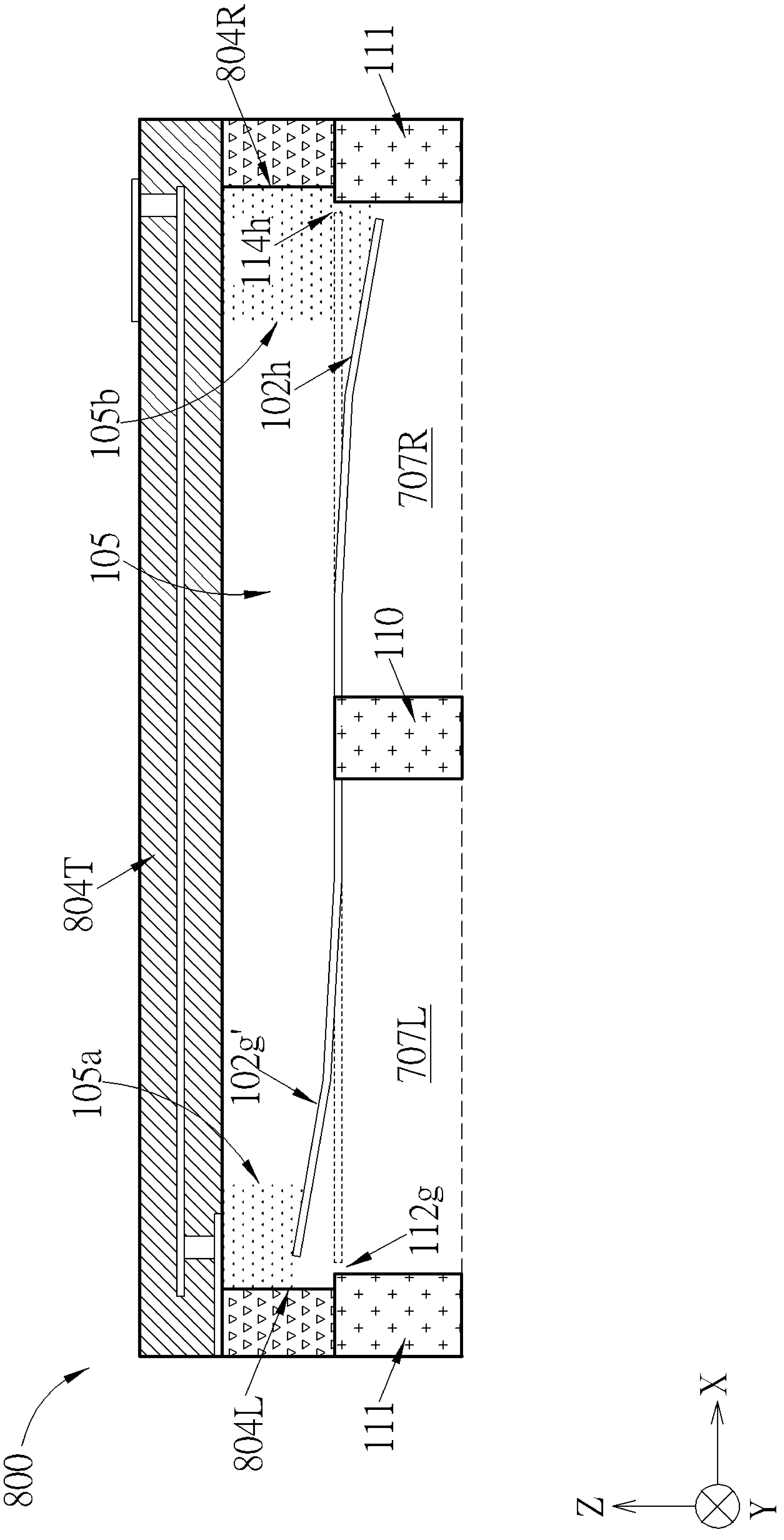

800
804L
111
112g
105a
102g'
707L
804T
110
105
707R
105b
102h
114h
804R
111
X
Y
Z

FIG. 9

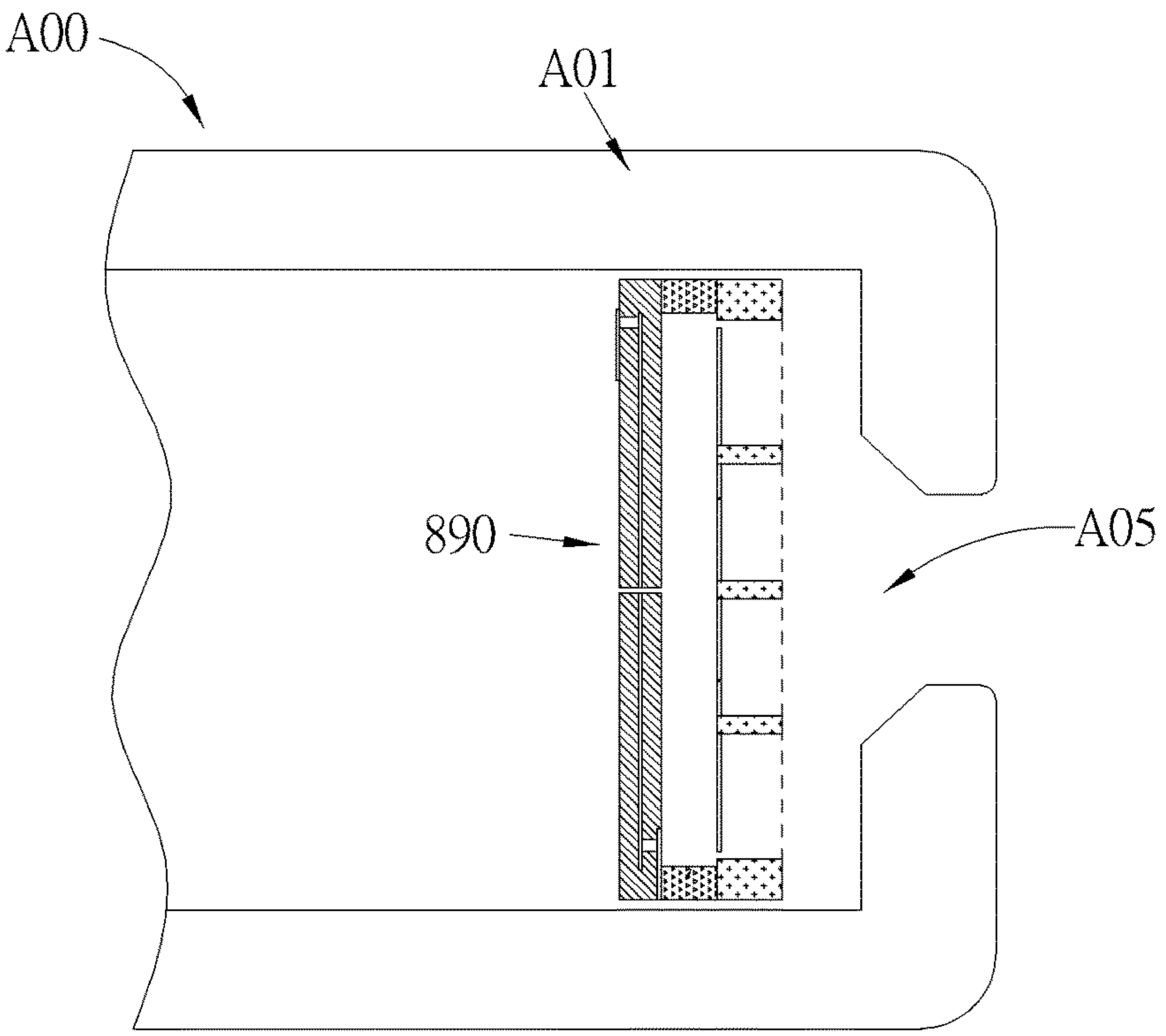


FIG. 10

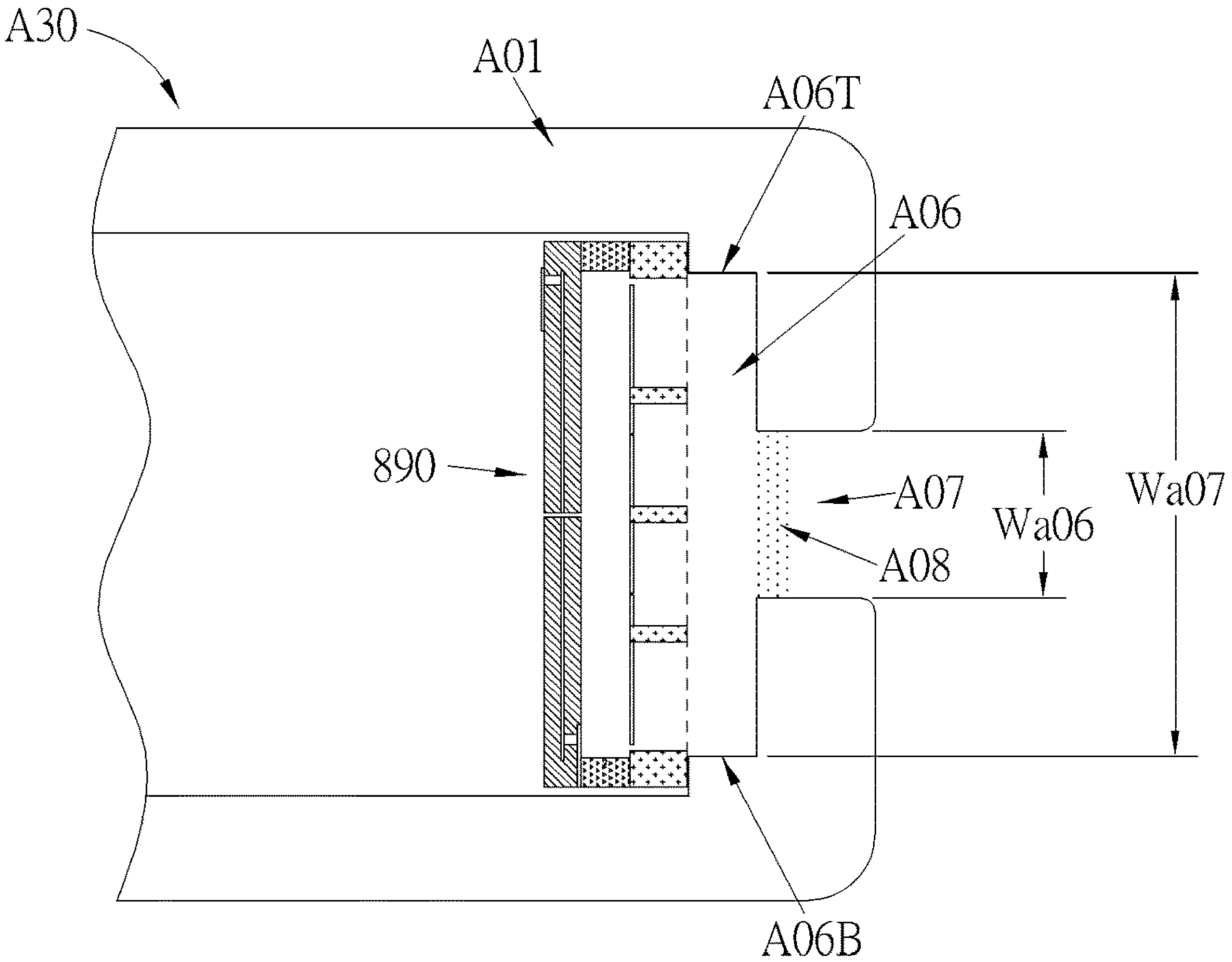


FIG. 11

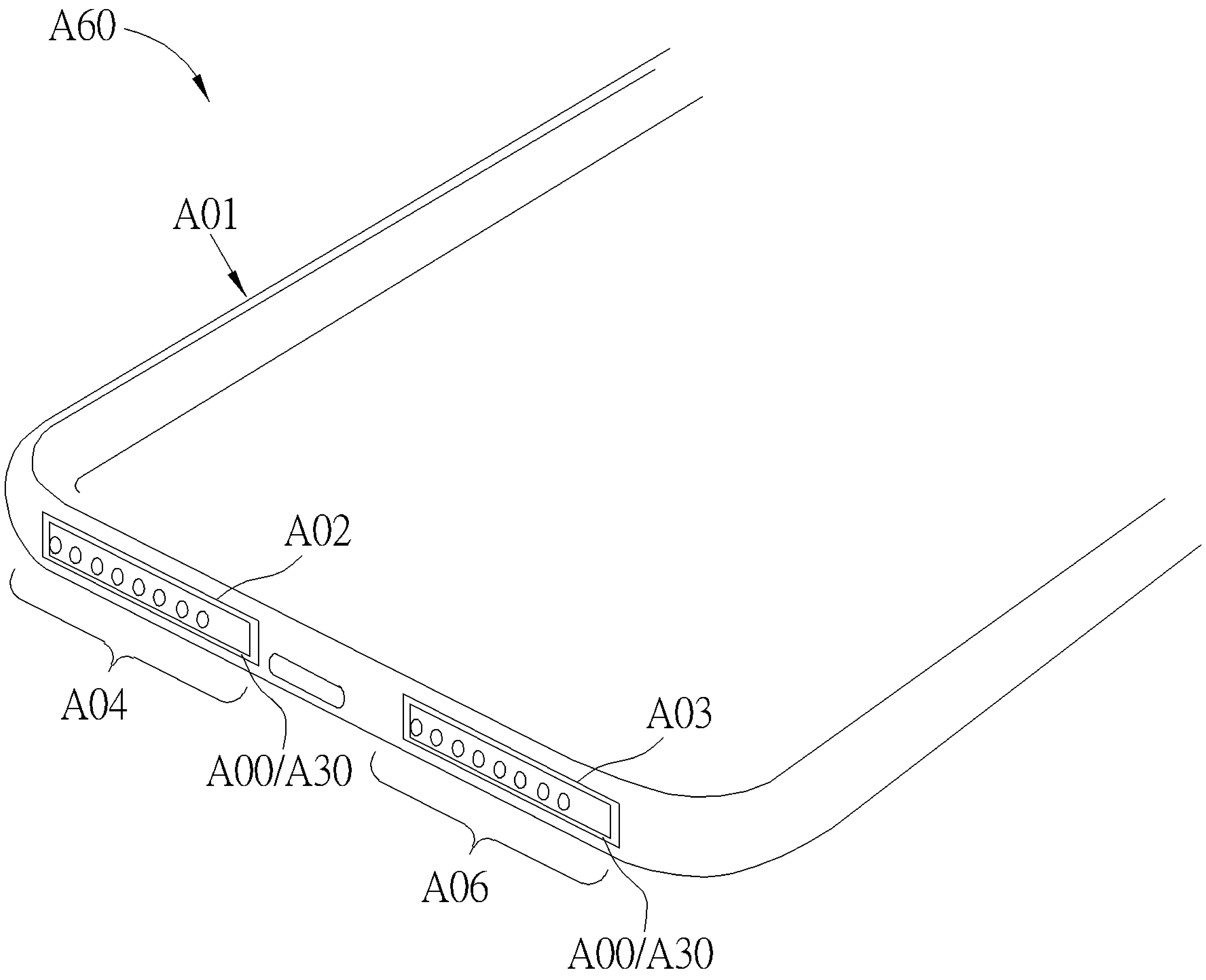


FIG. 12

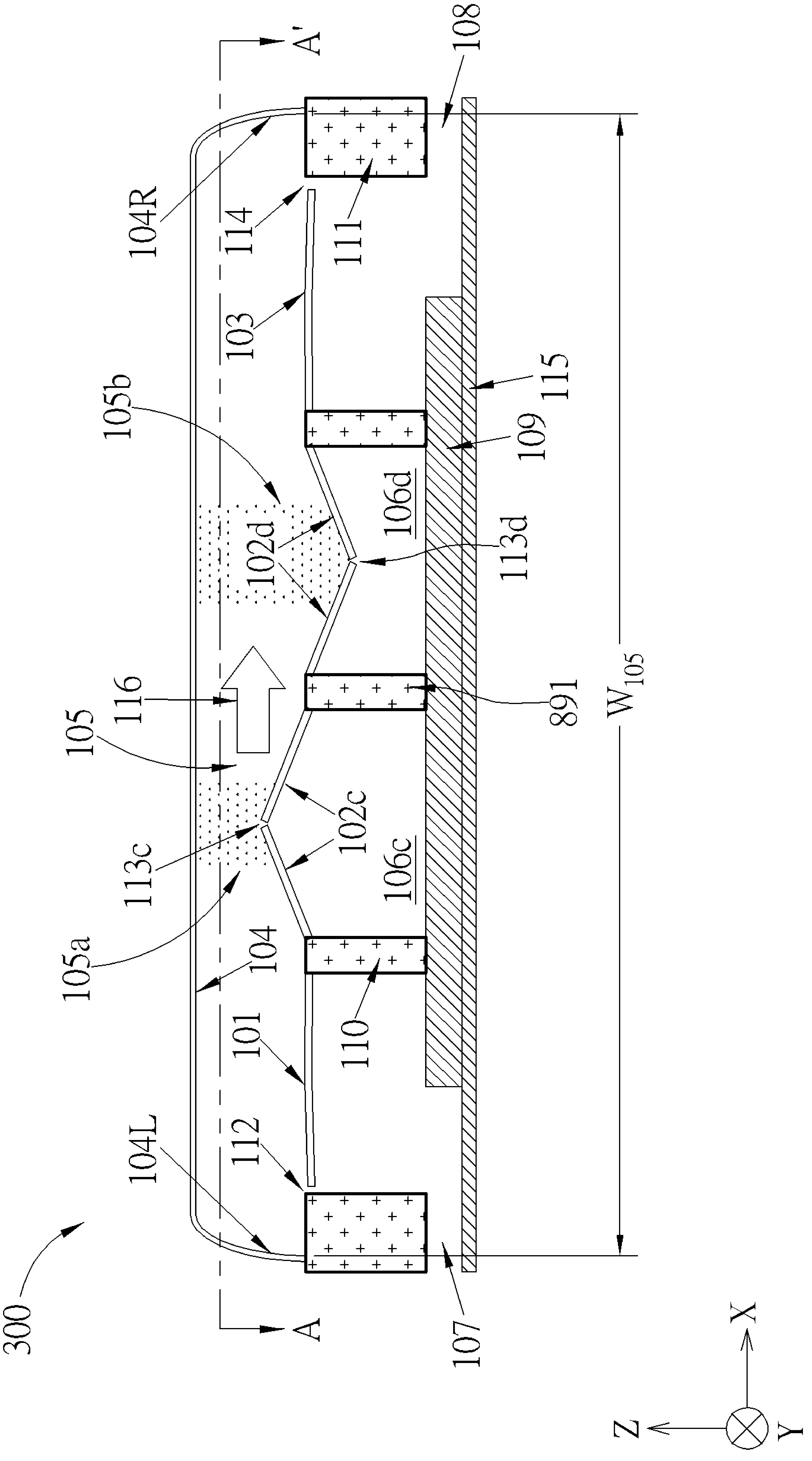

300
A
A'
104L
104R
104
105a
105
105b
116
113c
102c
102d
113d
106c
106d
101
103
112
114
110
111
891
109
115
107
108
W105
X
Y
Z

FIG. 13

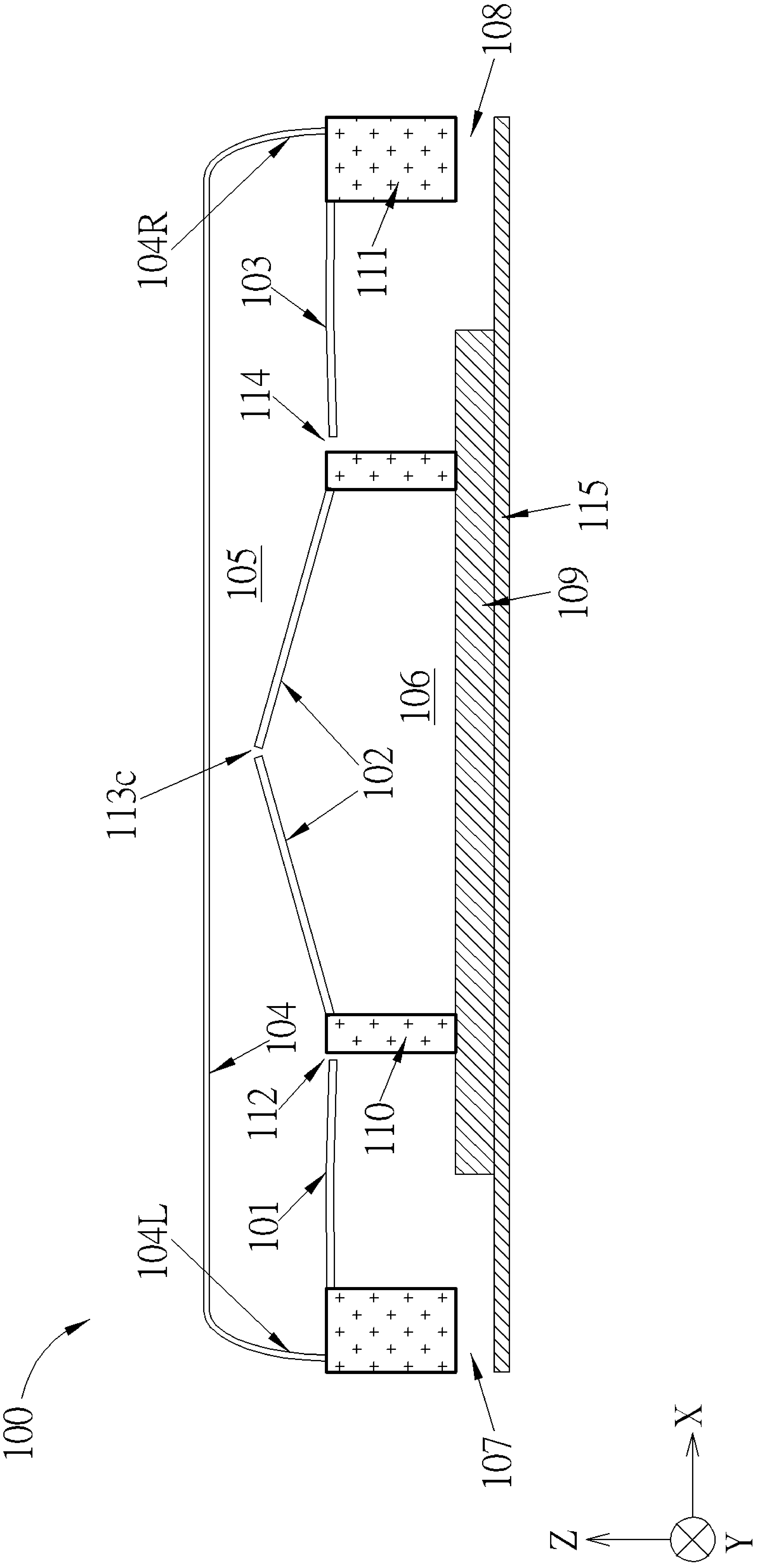

100
104L
104R
104
101
112
110
107
108
103
114
111
105
106
113c
102
102
115
109
X
Y
Z

FIG. 14

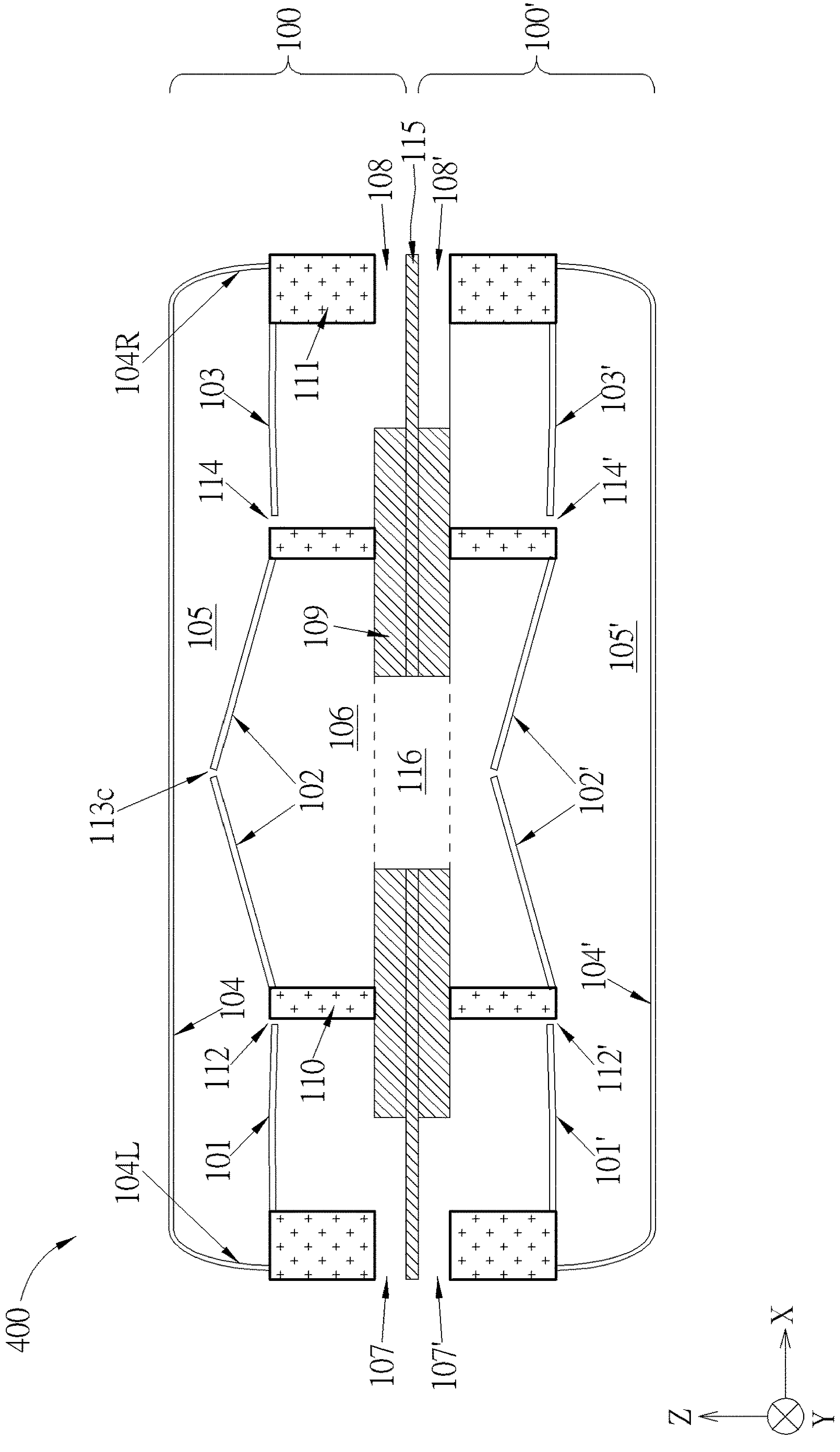

100
100'
115
108
108'
104R
111
103
103'
114
114'
105
109
105'
106
116
113c
102
102'
104
104'
112
112'
110
101
101'
104L
400
107
107'
X
Z
Y

FIG. 15

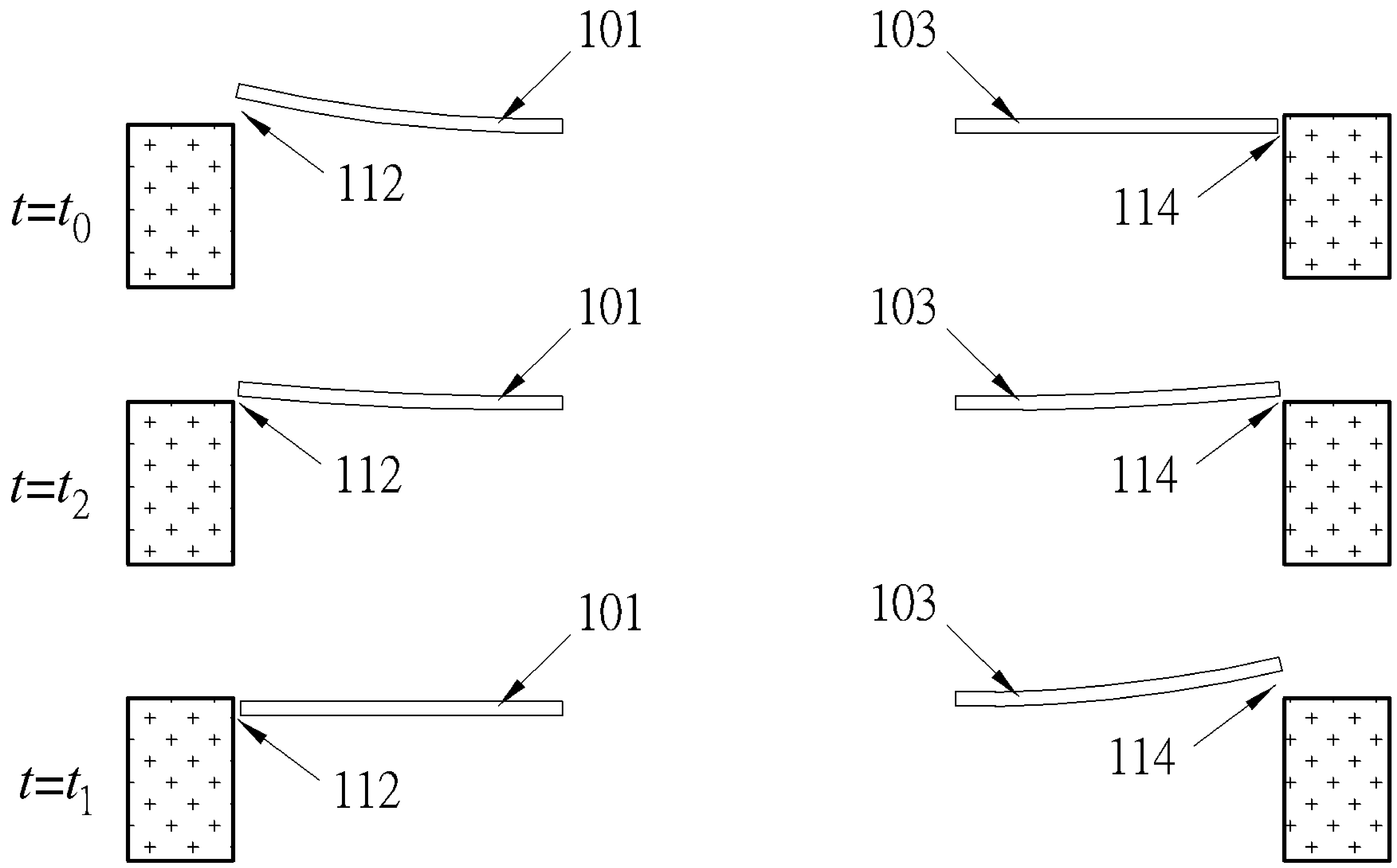


FIG. 16

AIR-PULSE GENERATING DEVICE AND SOUND PRODUCING METHOD THEREOF

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. provisional application No. 63/137,479 filed on Jan. 14, 2021, No. 63/138,449 filed on Jan. 17, 2021, No. 63/139,188 filed on Jan. 19, 2021, No. 63/142,627 filed on Jan. 28, 2021, No. 63/143,510 filed on Jan. 29, 2021, and No. 63/171,281 filed on Apr. 6, 2021, which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present application relates to an air-pulse generating device and a sound producing method thereof, and more particularly, to an air-pulse generating device and a sound producing method thereof capable of increasing overall air pulse rate, improving sound pressure level, and/or saving power.

2. Description of the Prior Art

Speaker driver and back enclosure are two major design challenges in the speaker industry. It is difficult for a conventional speaker to cover an entire audio frequency band, e.g., from 20 Hz to 20 KHz. To produce high fidelity sound with high enough sound pressure level (SPL), both the radiating/moving surface and volume/size of back enclosure for the conventional speaker are required to be sufficiently large.

Therefore, how to design a small sound producing device while overcoming the design challenges faced by conventional speakers is a significant objective in the field.

SUMMARY OF THE INVENTION

It is therefore a primary objective of the present application to provide an air-pulse generating device and a sound producing method thereof, to improve over disadvantages and/or restrictions of the prior art.

An embodiment of the present invention provides an air-pulse generating device, comprising a membrane structure and a valve structure; a cover structure, wherein a chamber is formed between the membrane structure, the valve structure and the cover structure; wherein an air wave vibrating at an operating frequency is formed within the chamber; wherein the valve structure is configured to be actuated to perform an open-and-close movement to form at least one opening, the at least one opening connects air inside the chamber with air outside the chamber; wherein the open-and-close movement is synchronous with the operating frequency.

Another embodiment of the present invention provides a sound producing method, applied in an air-pulse generating device, the method comprising forming an air wave within a chamber, wherein the air wave vibrates at an operating frequency, and the chamber is formed within the air-pulse generating device; and forming at least one opening on the air-pulse generating device at an opening frequency, wherein the at least one opening connects air inside the chamber with air outside the chamber; wherein the opening frequency is synchronous with the operating frequency.

These and other objectives of the present invention will no doubt become obvious to those of ordinary skill in the art after reading the following detailed description of the preferred embodiment that is illustrated in the various figures and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of an air-pulse generating device according to an embodiment of the present application.

FIG. **2** is a schematic diagram of a plurality of waveforms according to an embodiment of the present application.

FIG. **3** is a schematic diagram of a plurality of signals according to an embodiment of the present application.

FIG. **4** illustrates membrane driving signals according to an embodiment of the present application.

FIG. **5** is a schematic diagram illustrating a top view of the air-pulse generating device shown in FIG. **1**.

FIG. **6** and FIG. **7** are schematic diagrams of cross sectional views of air-pulse generating devices according to embodiments of the present application.

FIG. **8** and FIG. **9** are schematic diagrams of cross sectional views of air-pulse generating devices according to embodiments of the present application.

FIG. **10** and FIG. **11** are schematic diagrams of the air-pulse generating device shown in FIG. **8** disposed within constructs according to embodiments of the present application

FIG. **12** is a schematic diagram of a mobile device according to an embodiment of the present application.

FIG. **13** to FIG. **15** are schematic diagrams of cross sectional views of air-pulse generating devices according to embodiments of the present application.

FIG. **16** is a schematic diagram of valve movement according to an embodiment of the present application.

DETAILED DESCRIPTION

U.S. Pat. No. 10,425,732 provides a sound producing device, or an air-pressure-pulse-speaker (APPS), comprising a plurality of air pulse generating elements which is capable of producing a plurality of PAM (pulse-amplitude modulation) air pulses at an ultrasonic pulse rate, higher than a maximum human audible frequency. U.S. Pat. No. 10,425,732 also discloses that the APPS may function as a fan, which may be disposed within an electronic device and help on heat dissipation of the electronic device.

U.S. Pat. No. 10,771,893 provides a SEAM (single ended amplitude modulation) driving signal for a sound producing device, or an APPS, capable of producing single-ended PAM air pulses at ultrasonic pulse rate, in order to further enhance the sound pressure level performance and low audio frequency response. The SEAM driving signal comprises a plurality of electrical pulses, where the plurality of electrical pulses has the same polarity compared to (or with respect to) a certain voltage. For SEAM driving signal, each electrical pulse cycle comprises a PAM (pulse, amplitude-modulated) phase and an RST (reset) phase, which will be illustrated later on. The SEAM driving signal may be a PAM signal within the PAM phase and return to a reset voltage within the RST phase.

U.S. application Ser. No. 16/802,569 provides a sound producing device, or an APPS, which produces air pulses via chamber compression/expansion excited by membrane movement and the air pulses are propagated via through pressure ejection orifices (PEOs) formed either on the membrane or on a plate of the sound producing device, in order to achieve significant air pressure with small size/dimension of the sound producing device.

U.S. Pat. No. 11,043,197 provides an air pulse generating element and an APPS which utilize membrane to perform compression/expansion of the air within a chamber, and utilizes slits formed on the membrane to form virtual valves which may open temporarily to provide air shunt, such that an air pressure balancing process between two sides of membrane is accelerated.

In an embodiment, the air-pulse generating device of the present application may be applied in an APPS application, which is configured to produce PAM air pulses at an ultrasonic pulse rate according to APPS sound production principle. In another embodiment, the air-pulse generating device of the present application may be applied in an air movement or fan application, which functions as a fan and is similar to U.S. Pat. No. 10,425,732.

FIG. **1** is a schematic diagram of a cross sectional view of an air-pulse generating device **890** according to an embodiment of the present application. The air-pulse generating device **890** may be applied within an APPS. The air-pulse generating device **890** comprises a membrane structure **12**, a valve structure **11** and a cover structure **804**. A chamber **105** is formed between the membrane structure **12**, the valve structure **11** and the cover structure **804**. The air-pulse generating device **890** produces its (air pressure) output at ports **707**L and **707**R. FIG. **1** illustrates (solid outlines) the membrane structure **12** in a state in which the membrane structure **12** is (substantially) flat and parallel to XY-plane, and also illustrates (dashed outlines) the membrane structure **12** in an actuated state in which the membrane structure **12** is curved.

The membrane structure **12** and the valve structure **11** may have thin film structure, which may, e.g., be fabricated by MEMS (Micro-Electro-Mechanical System) fabrication process using SOI (silicon/Si of insulator) or POI (Poly-Si/polysilicon on insulator) wafers, but not limited thereto. In the embodiment shown in FIG. **1**, the membrane structure **12** comprises a first membrane portion **102***a* and a second membrane portion **102***b*. The valve structure **11** comprises a first valve portion **101** and a second valve portion **103**. The cover structure **804** comprises a top plate **804**T and side walls **804**L and **804**R. The chamber **105** is surrounded by/between the membrane portions **102***a* and **102***b*, the valve portions **101** and **103**, the top plates **804**T, and the side walls **804**L and **804**R. Valve portion **101**/**103** is anchored to support structure **110**/**115** on one end and is free-moving on the other end, where the free-moving end is located close/next to side wall **804**L/**804**R.

The membrane structure **12** is configured to be actuated, such that an air wave AW is produced. Furthermore, by carefully choosing driving signal(s) fed to the membrane structure **12**, the air wave AW may vibrate at an operating frequency f_{CY} and propagates along with a direction (e.g., X-direction) parallel to the membrane structure **12** within the chamber **105**.

In a perspective, air wave may be related that the mass of air molecules periodically moves in a back-and-forth direction (e.g., left-and-right in X-direction, in view of X-axis components movement) at a certain time period due to air pressure variation or variation of air-molecule density. Air wave vibrating at a certain frequency may be related to the operating frequency f_{CY} that the certain frequency is a reciprocal of the certain time period, and vice versa.

The valve structure **11** is configured to be actuated to perform an open-and-close movement, at an opening frequency, to form at least one opening periodically, where the at least one opening connects the air inside the chamber **105** with the ambient/air outside the chamber **105**. Specifically, the valve portion **101** may be actuated to perform an up-and-down movement (in the Z direction) which cause an opening **112** to form-and-unform, and this is referred to as the open-and-close of valve **101**. Similarly, the valve portion **103** may be actuated to perform an up-down movement (in the Z direction) which cause an opening **114** to form-and-unform, and this is referred to as the open-and-close of valve **103**. The open-and-close movements of the valve structure **11**, including the valve (portions) **101** and **103**, (or the opening frequency) would be synchronous with the air wave AW, which is further synchronous with the operating frequency f_{CY}. The open-and-close movements of the valve structure/portion being synchronous with the operating frequency f_{CY} means that, the open-and-close movements of the valve portion/structure is performed (preferably) at the operating frequency f_{CY}, or at a frequency of $(M/N)*f_{CY}$, wherein both M and N are integers. The open-and-close, up-and-down, form-and-unform movement will be elaborated later. In the following description, the valve portion **101**/**103** may be referred to the valve **101**/**103** for brevity.

The function of valve opening is similar to that of a variable resistor whose resistance to airflow, Z_{VALVE}, is controlled by the degree of the valve opening. When the valve is closed, i.e. $Z101<Z_{O/C}$ or $Z103<Z_{O/C}$, the magnitude of Z_{VALVE} will be high (Hi-Z). When the valve is opened, i.e. $Z101>Z_{O/C}$ or $Z103>Z_{O/C}$, the magnitude of Z_{VALVE} will be inversely related to the degree of opening, or $Z101-Z_{O/C}$ or $Z103-Z_{O/C}$. The wider a valve is opened, the lower the value of Z_{VALVE} will be and the higher the airflow will be for any given chamber pressure.

Chamber Resonance

Note that, given the side walls **804**L and **804**R may serve as reflection walls, the air wave AW generated by the membrane structure **12** may comprise an incident wave and a reflected wave. In an embodiment, a width of the chamber **105**, denoted as W_{105}, or a distance between the side walls **804**L and **804**R, may be designed such that, the incident wave and the reflected wave may be aggregated and form a standing wave within the chamber **105**.

In an embodiment, the distance between the side walls **804**L and **804**R or the width W_{105} may equal to an integer multiple of a half wavelength ($\lambda/2$) corresponding to the operating frequency f_{CY} of the air wave AW, $\lambda=C/f_{CY}$, where C is the speed of sound.

In an embodiment, the distance between the side walls **804**L and **804**R or the width W_{105} may be designed such that, a 1st mode (or n=1 mode) resonance, also called fundamental mode resonance or 1st harmonic resonance, is formed within the chamber **105**. In this case, only 1 air-motion antinode (amplitude reaches peak) exists within the chamber **105** (which may be at a center of the chamber **105**); only 2 air-motion nodes (amplitude near 0) locate at the side walls **804**L and **804**R; only 1 air-pressure node exists within the chamber **105** (which may be at the center of the chamber **105**); only 2 air-pressure antinodes locate at the side walls **804**L and **804**R.

Herein, in chamber resonance or standing wave perspective, the air-motion antinode represents position at which amplitude of air-molecule velocity/displacement achieves maximum in air-motion over X-axis within the chamber; the air-motion node represents position at which amplitude of air-molecule velocity/displacement achieves minimum in air-motion over X-axis within the chamber (usually 0 movement); the air-pressure antinode represents position at which amplitude of air pressure variation achieves maximum in air pressure over X-axis within the chamber; the air-pressure node represents position at which amplitude of air pressure variation achieves minimum in air pressure over X-axis within the chamber.

In FIG. **1**, curves U**102** schematically represent displacements of air particles distributed in the X-direction at different times, curves W**102** schematically represent pressure distribution within the chamber at different times. For example, dashed lines of the curves U**102** and W**102** are corresponding to a time t_0 and solid lines of the curves U**102** and W**102** are corresponding to a time t_1. P**0** in FIG. **1** may refer to an ambient pressure, which may be 1 atm. In an embodiment, to achieve 1^{st} mode (or n=1 mode) resonance, the distance between the between the side walls **804**L and **804**R or the width W_{105} may be one half wavelength ($\lambda_{CY}/2$) corresponding to the operating frequency f_{CY} of the air wave AW.

Details of the valve movement of **101**/**103** are further illustrated in FIG. **16**. At the time t_0 (or when $t=t_0$), the valve **101** is actuated to bend upward such that the opening **112** is opened or formed, and the valve **103** may be actuated to (substantially) seal the opening **114**, which means that the opening **114** is closed or unformed, as shown in the top of FIG. **16**. On the other hand, at the time t_1 (or when $t=t_1$), the valve **101** may be actuated to (substantially) seal the opening **112**, which means that the opening **112** is closed or unformed, and the valve **103** is actuated to bend upward such that the opening **114** is opened or formed, as shown in the bottom of FIG. **16**. In an embodiment, at some time t_2 (or when $t=t_2$, where $t_2 \neq t_0$ and $t_2 \neq t_1$), the valves **101** and **103** are in a state where the openings **112** and **114** are barely opened or barely closed, as shown in the middle of FIG. **16**, corresponding to $Z101=Z_{O/C}$ and $Z103=Z_{O/C}$ as shown in FIG. **2** respectively.

FIG. **2** is a schematic diagram of a plurality of waveforms according to an embodiment of the present application. Waveform Z**101** schematically represents displacement in Z-direction of the free-moving end of valve portion **101**; while waveform Z**103** schematically represents displacement in Z-direction of the free-moving end of valve portion **103**. $Z_{O/C}$ represents a certain level of displacement, and the suffix O/C stands for a line separating the open-state from the close-state. When the displacement of the free-moving end of valve Z**101** is larger than (above) the displacement level $Z_{O/c}$, the opening **112** is formed or the valve **101** is opened. When the displacement of the free-moving end of valve Z**103** is larger than the displacement level $Z_{O/C}$, the opening **114** is formed or the valve **103** is opened. When the displacement of the free-moving end of valve Z**101** is less than (below) the displacement level $Z_{O/C}$, the opening **112** is not formed or the valve **101** is closed. When the displacement of the free-moving end of valve Z**103** is less than the displacement level $Z_{O/C}$, the opening **114** is not formed or the valve **103** is closed.

Waveform P**112** schematically represents air pressure at the opening **112** (within the chamber **105**). Waveform P**114** schematically represents air pressure at the opening **114** (within the chamber **105**). Waveform Z**102***a* represents displacement of the membrane portion **102***a*, which may share similar waveform with P**112**. Waveform Z**102***b* represents displacement of the membrane portion **102***b*, which may share similar waveform with P**114**. Waveform P**707**L schematically represents air pressure (or quantity analogous to air pressure) at the port **707**L (out of the chamber **105**). Waveform P**707**R schematically represents air pressure (or quantity analogous to air pressure) at the port **707**R (out of the chamber **105**). Waveform P**890** represents a sum/superposition of P**707**L and P**707**R, corresponding to an aggregated on-axis output acoustic pressure of the device **890**. Waveform Z**102***a*/Z**102***b* whose unit is length, such as μM, generally has different amplitude from waveform P**112**/P**114** whose unit is pressure, such as Pa. However, since the purpose of FIG. **2** is mainly to illustrate the timing relationship between different parts of the operation, these waveforms are merged in FIG. **2** for brevity.

FIG. **3** is a schematic diagram of a plurality of signals according to an embodiment of the present application. S_{IN} represents an input audio signal. S**101**/S**103** represents a valve driving signal configured to drive the valve portion **101**/**103**. S**102***a*/S**102***b* represents a membrane driving signal configured to drive the membrane portion **102***a*/**102***b*.

AM Modulation Waveform

As can be seen from the plots/waveforms P**112** and P**114** in FIGS. **2**, P**112** and P**114** are/comprise amplitude-modulated waveforms, and amplitude-modulated waveform P**112**/P**114** may be expressed as a product of a carrier component and a modulation component, in general. The carrier component, usually expressed as $\cos(2\pi f_{CY}t)$, oscillates at the operating frequency f_{CY}, where $f_{CY}=1/T_{CY}$, where T_{CY} (denotes an operating cycle. The modulation component, may be expressed as m(t), is reflected by an envelope of the amplitude-modulated waveform (denoted by dotted envelope-curves in FIG. **2** and FIG. **3**) which is corresponding to the input audio signal S_{IN}. In an embodiment, the modulation component m(t) may be corresponding or proportional to the input audio signal S_{IN}.

The amplitude-modulated waveform P**112**/P**114** may be achieved by driving the membrane structure **12** by pulse-amplitude modulated driving signal. For example, the membrane driving signal S**102***a*/S**102***b* shown in FIG. **3** driving the membrane portion **102***a*/**102***b* are pulse-amplitude modulated signal, generated according to the input audio signal S_{IN}.

Membrane Driving Signal

In other words, the membrane driving signal S**102***a* comprises a first pulse-amplitude modulated (PAM) signal comprising a plurality of first pulses with respect to a certain bias voltage V_B. The first pulses are temporally distributed/arranged by the operating frequency f_{CY}. Similarly, the membrane driving signal S**102***b* comprises a second PAM signal comprising a plurality of second pulses with respect to the bias voltage V_B. The second pulses are temporally distributed/arranged by the operating frequency f_{CY}.

In addition, the first pulses comprise first transition edges; while the second pulses comprise second transition edges. The first transition edges of the first pulses within the PAM signal S**102***a* coincide with the second transition edges of the second pulses within the PAM signal S**102***b*. Furthermore, at a certain coincidence time of the first transition edge and the second transition edge, the first transition edge is corresponding to a first transition polarity, and the second transition edge is corresponding to a second transition polarity. The first transition polarity is opposite to the second transition polarity, at the certain coincidence time. Details of the coincidence of the first and second transition edges and the opposition of the first and second transition polarities may be referred to FIG. **3** of the present application, or also be referred to U.S. Pat. No. 11,043,197 or No. U.S. Pat. No. 11,051,108, which are not narrated herein for brevity.

Note that, the membrane driving signal S**102***a*/S**102***b* driving the membrane portion **102***a*/**102***b* is bipolar (or double-ended) with respect to the bias voltage V_B, which is not limited thereto. For example, FIG. **4** illustrates a 2^{nd} type of membrane driving signals S**102**a' and S**102**b'. The membrane portions **102**a and **102**b may be driven by the membrane driving signals S**102**a' and S**102**b', respectively. Note that, the membrane driving signals S**102**a' and S**102**b' are SEAM driving signals, which are unipolar with respect to the bias voltage V_B. Similar to the unipolar membrane driving signals S**102**a and S**102**b, first pulses within the driving signal S**102**a' and second pulses within the driving signal S**102**b' are mutually interleaved, and have coincidence transition edges and opposite transition polarities, as shown in FIG. **4**. Details of the unipolar SEAM driving signal may be referred to U.S. Pat. No. 10,771,893, which are not narrated herein for brevity.

FIG. **4** also illustrates a 3rd type of membrane driving signals S**102**a" (solid line in the bottom) and S**102**b" (dashed line in the bottom, together with S**102**a"). In an embodiment, the membrane portion **102**a may be driven by the membrane driving signal S**102**a" and the membrane portion **102**b may be driven by the membrane driving signal S**102**b". The driving signal S**102**b" may be obtained from S**102**a" according to equations expressed as S**102**b"=V_B-S**102**a" (eq. 1) or S**102**b"=−S**102**a" (eq. 2). In other words, a sum of the membrane driving signals S**102**a" and S**102**b" may be a constant. The constant may be the voltage level V_B (if eq. 1 is applied) or 0V (if eq. 2 is applied). Similar to the membrane driving signals S**102**a and S**102**b, first pulses within the driving signal S**102**a" and second pulses within the driving signal S**102**b" have coincidence transition edges and opposite transition polarities, which may be observed from FIG. **4**.

Pressure Gradient

In one perspective, during a first interval (which may be a first half of the operating cycle T_{CY}), by applying the membrane driving signal pair (S**102**a, S**102**b)/(S**102**a', S**102**b')/(S**102**a", S**102**b") to the membrane portions **102**a and **102**b, the membrane portions **102**a may be actuated to move toward a positive Z direction and the membrane portions **102**b may be actuated to move toward a negative Z direction. Hence, during the first interval, the membrane portion **102**a may be actuated to compress a first part/volume **105**a (on top of the membrane portion **102**a) within the chamber **105** and the membrane portions **102**b may be actuated to expand a second part/volume **105**b (on top of the membrane portion **102**b) within the chamber **105**, such that a first air pressure gradient (indicated by the block arrow **116** in FIG. **1**) is formed from the first part/volume **105**a toward the second part/volume **105**b.

Conversely, during a second interval (which may be a second half of the operating cycle T_{CY}), the membrane portions **102**b may be actuated to move toward the positive Z direction and the membrane portions **102**a may be actuated to move toward the negative Z direction. Hence, during the second interval, the membrane portion **102**b may be actuated to compress the second part/volume **105**b and the membrane portions **102**a may be actuated to expand the first part/volume **105**a, such that a second air pressure gradient (opposite to **116**, not shown in FIG. **1**) is formed from the second part/volume **105**b toward the first part/volume **105**a.

A pressure-gradient direction of the air pressure gradient (e.g., **116** shown in FIG. **1**) generated by the membrane structure **12**, including the membrane portions **102**a and **102**b, is parallel to the X-direction shown in FIG. **1**. A propagation direction of the air wave AW propagating within the chamber **105** is also parallel to the X-direction. That is, the pressure-gradient direction is parallel to the air-wave propagation direction. In addition, the pressure-gradient direction, which is parallel to the X-direction, is perpendicular to a membrane displacement direction of the membrane structure **12**, largely in the Z-direction, wherein the membrane displacement direction refers to a direction which the membrane is actuated to move toward. Therefore, the pressure-gradient direction is parallel to the XY-plane, the plane of the membrane structure, and is orthogonal to the direction of the membrane displacements (Z). By taking the membrane structure being actuated or deformed into consideration, the pressure-gradient direction (generated by the membrane structure) may be regarded as being substantially parallel to the membrane structure and/or substantially perpendicular/orthogonal to the direction of the membrane displacements/movement.

Spatial Location of Valve Opening

When a standing wave is formed within chamber **105**, in order to enhance the acoustic output efficiency, the opening(s) is suggested to be located at or near the air-pressure antinode(s) of the standing wave. For the air-pulse generating device **890**, the opening may be formed spatially on a location where a peak of the air/standing wave is achieved, wherein the peak of the air/standing wave herein may be in terms of air pressure (for APPS application).

For APPS application, suppose that air pressure within the chamber may be expressed as a single-variable function p(x) or a two-variable function p(x, t), where x denotes variable in X-axis and t denotes variable in time-axis. The peak may be corresponding to a place where the 1st order (partial) derivative being zero, i.e., dp(x)/dx=0 or ∂p(x, ∂x=0 (to seek optimum spatial location of valve opening). In other words, (for some fixed time t_0) the peak may be interpreted as a local maximum or a local minimum of p(x)/p(x, t_0) over x-axis.

In this case, for the air-pulse generating APPS device **890**, the openings **112** and **114** are formed near the side walls **804**L and **804**R, since the air-pressure antinodes of standing wave will be located at the side walls **804**L and **804**R.

Temporal Alignment of Valve Opening

In another aspect, in order to enhance the air pulse generation efficiency, the timing of valve opening(s) is suggested to be formed during an interval in which a peak pressure of the air wave is achieved at the locations of the valve opening, such as illustrated by **112** and **114** of FIG. **1**. The peak pressure timing herein may be corresponding to a time at which the 1st order (partial) time derivative is zero, i.e., dp(t)/dt=0 or ∂p(x, t)/∂t=0 (to seek optimum timing, i.e., temporal behavior, of valve opening), given that air pressure within the chamber may be expressed as a single-variable function p(t) or the two-variable function p(x, t). In other words, (for some fixed location x_0, x_0 may be the location of valve opening **112** or **114**) the peak may be interpreted as a local maximum or a local minimum of p(x)/p(x_0, t) over t-axis.

For example, referring to FIG. **2**, time intervals of the opening **112** being formed (i.e., the valve portion **101** being actuated to be opened or the valve **101** being opened) is illustrated as dotted regions in the plot Z**101**; time intervals of the opening **114** being formed (i.e., the valve portion **103** being actuated to be opened or the valve **103** being opened) is illustrated as cross hatched regions in the plot Z**103**. The opening **112** is formed during a (first) interval T_1; while the opening **114** is formed during a (second) interval T_2. Both intervals T_1 and T_2 may lie within the operating cycle T_{CY}, meaning that $T_1<T_{CY}$, $T_2<T_{CY}$ and $T_1+T_2 \le (1+d)\times T_{CY}$, where $T_{CY}=1/f_{CY}$ and $d<0.5$.

To enhance efficiency, the first opening **112** is formed within the first interval T_1 during which a first peak pressure pk_1 of the air wave AW at a first location (corresponding to the sidewall **804**L) is achieved; the second opening **114** is formed within the second interval T_2 during which a second peak pressure pk_2 of the air wave AW at a second location is achieved.

In one perspective, the opening frequency of the valves **101** and **103** equals the operating frequency f_{CY}, in the embodiment shown in FIG. **2**.

Note that, in the embodiment illustrated in FIG. **2**, the first interval T_1 (representing the opening interval of the valve **101**) covers one half of the operating cycle T_{CY}, and the second interval T_2 (representing the opening interval of the valve **103**) covers another half of the operating cycle T_{CY}, meaning that $T_1=T_2\approx T_{CY}/2$ (i.e., let a length of interval T_y be equal to half the length of the operating cycle T_{CY}, then $T_y\approx T_1$ or $T_y\approx T_2$), which is not limited thereto. The interval T_1 or T_2 may be slightly shorter or longer than $T_{CY}/2$ (for example, within ±10% or ±20%). As long as the opening interval of the valve **101** covers the first peak pk_1 and the opening interval of the valve **103** covers the second peak pk_2, the requirements of present application are satisfied, which is within the scope of the present application.

Furthermore, the first interval T_1 (representing the opening interval of the valve **101**) may cover a first over/under-pressure interval during which air pressure P**112**, produced by the membrane movement, is greater/smaller than a certain pressure P_{th}, where the first over/under-pressure interval overlaps with T_1 in the embodiment illustrated in FIG. **2**. Similarly, the second interval T_2 (representing the opening interval of the valve **103**) may cover a second over/under-pressure interval during which air pressure P**114**, produced by the membrane movement, is greater/smaller than the certain pressure P_{th}, where the second over/under-pressure interval overlaps with T_2 in the embodiment illustrated in FIG. **2**. In this case, the air-pulse generating device **890** generate positive/negative air pulses during the valve opening intervals T_1 and T_2, where the positive/negative air pulses herein may be propagated from the chamber **105** to ambient during the valve opening interval(s).

Note that, the AW pressure wave generated by driving waveform S**102***a*'/S**102***b*' of FIG. **4** will be simple AM while the AW pressure wave generated by driving waveform S**102***a*/S**102***b* of FIG. **3** or S**102***a*"/−S**102***a*" of FIG. **4** will be DSB-SC (double-sideband, suppress carrier). The timing relationship shown in FIG. **2** corresponds to a simple AM modulated AW pressure wave and peaks pk**1**, pk**2** will not cross the line of P_{th}. However, for DSB-SC modulated AW pressure wave, pk**1**, pk**2** will cross the line of P_{TH} whenever the polarity of S_{IN} changes, at which time over-pressure becomes under-pressure and vice versa.

Note that, the total pressure within the chamber may have two component pressures: one is produced by the membrane movement, the other is produced by the valve movement. Either of both components may be in the form of standing wave. The pressures P**112** and P**114** shown in FIG. **2** only refer to component pressures produced by the membrane movements.

Synchronous Valve Opening

Furthermore, the valve portion **101** may form the opening **112** in/during a plurality of first valve opening intervals, and the air pressure P**112** may be greater than the certain pressure P_{th} in/during a plurality of first over-pressure intervals. In the embodiment shown in FIG. **2**, the plurality of first valve opening intervals (of the valve **101**) and the plurality of first over-pressure intervals (of pressure P**112**) are temporally aligned or overlapped, where the first valve

opening intervals (of the valve **101**) and the first over-pressure intervals (of pressure P**112**) are annotated as T_1 in FIG. **2**.

Similarly, the valve portion **103** may form the opening **114** in/during a plurality of second valve opening intervals and the air pressure P**114** may be greater than the certain pressure P_{th} in a plurality of second over-pressure intervals. The plurality of second valve opening intervals (of the valve **103**) and the plurality of second over-pressure intervals (of pressure P**114**) may be also temporally aligned or overlapped, where the valve opening intervals (of the valve **103**) and the over-pressure intervals (of pressure P**114**) are annotated as T_2 as in FIG. **2**.

In the present application, a plurality of first time intervals and a plurality of second time intervals being temporally aligned or overlapped may refer that, 1) the plurality of first time intervals and the plurality of second time intervals are temporally arranged (or temporally appear) at the same frequency; or 2) a first time interval and a second time interval with which the first time interval overlaps, forming an overlapped region, and a length of the overlapped region is at least 50% of a length of the first (or second) time interval.

By aligning the valve opening intervals and the over-pressure intervals, the air-pulse generating device **890** may produce a plurality of first air pulses AP_1 (shown as P**707**L in FIG. **2**) at the port **707**L via the opening **112**, and produce a plurality of second air pulses AP_2 (shown as P**707**R in FIG. **2**) at the port **707**R via the opening **114**. In addition, a time corresponding to the peak valve opening of Z**101**/Z**103** is preferably aligned to a time corresponding to the peak pressure of P**112**/P**114** produced by the membrane movement.

In different perspectives, T_1 in FIG. **2** may denote, respectively: the first valve opening intervals of the valve **101** (in Z**101**'s perspective); first membrane movement intervals of the membrane portions **102***a* (in Z**102***a*'s perspective) and **102***b* (in Z**102***b*'s perspective), creating a pressure gradient (vector) directing from volume **105***a*, atop membrane portion **102***a*, towards volume **105***b*, atop membrane portion **102***b*; the first over-pressure intervals (in P**112**'s perspective); and first duty periods of the first air pulses at port **707**L, AP_1. Similarly, T_2 in FIG. **2** may denote, respectively: the second valve opening intervals of the valve **103** (in Z**103**'s perspective); second membrane movement intervals of the membrane portions **102***a* (in Z**102***a*'s perspective) and the membrane portion **102***b* (in Z**102***b*'s perspective), creating a pressure gradient (vector) directing from volume **105***b*, atop membrane portion **102***b*, towards volume **105***a*, atop membrane portion **102***a*; the second over-pressure intervals (in P**114**'s perspective), and second duty periods of the second air pulses at port **707**R, AP_2.

FIG. **2** illustrates, the first valve opening intervals of the valve **101**, the first chamber pressure gradient intervals, the movements of membrane portions **102***a* and **102***b*, the first over-pressure intervals and the first duty periods of the first air pressure pulses AP_1 are temporally aligned (peak-to-peak) and overlapped (period wise). Similarity, the second valve opening intervals of the valve **103**, the second chamber pressure gradient intervals, the movements of membrane portions **102***a* and **102***b*, the second over-pressure intervals (in P**114**'s perspective), and the second duty periods of the second air pressure pulses AP_2 are temporally aligned (peak-to-peak) and overlapped (period wise).

Combining Two Half-Wave Rectified Pulses into One Full-Wave Rectified Pulses

In a perspective, by comparing waveforms P**112** and P**707**L, P**707**L may be interpreted as a half-wave rectified version of P**112**, rectified by the timing varying impedance associated with valve **101** movement Z**101**. Also, by comparing waveforms P**114** and P**707**R, P**707**R may be interpreted as a half-wave rectified version of P**114**, rectified by the timing varying impedance associated with valve **103** movement Z**103**. The waveform P**890**, the summing the waveforms P**707**L and P**707**R and representing the on-axis output acoustic pressure of the device **890**, may be interpreted as a full-wave rectified version of P**112** or P**114**.

Referring to plot P**707**L, the plurality of first air pulses AP_1 are produced at a first (air) pulse rate APR_1 corresponding to the operating frequency f_{CY}. Referring to plot P**707**R, the plurality of second air pulses AP_2 are produced at a second (air) pulse rate APR_2 corresponding to the operating frequency f_{CY}.

Referring to plot P**890**, since the first plurality of air pulses AP_1 and the second plurality of air pulses AP_2 are temporally and mutually interleaved, it can be interpreted that the air-pulse generating device **890** produces a plurality of aggregated air pules AP. The plurality of aggregated air pules AP comprises the first air pulses AP_1 with the first pulse rate APR_1 and the second air pulses AP_2 with the second pulse rate APR_2. The aggregated air pules AP is produced at an overall (air) pulse rate PRO.

Under a condition of $APR_1=APR_2=f_{CY}$ as the embodiment illustrated in FIG. **2**, the overall pulse rate PRO is twice of the pulse rate APR_1 (or APR_2). In other words, the overall pulse rate PRO is corresponding to twice of the operating frequency f_{CY}, i.e., $PRO=2*f_{CY}$, analogous to 60 Hz 110 VAC sine waveform will produce 120 Hz of half-sine waveform after being full-wave rectified.

Analogy to AM Radio Demodulation

In a perspective, the action of the membrane movement can be compared to the AM radio station which creates EM wave amplitude modulated by sound signal and radiates the AM EM wave into the air. Instead of EM wave, device **890** generates amplitude modulated ultrasound wave and transmits such AM ultrasound wave into chamber **105**. Such ultrasound wave is further amplified, at the location of the valve, by the standing wave construct of chamber **105**. The standing wave construct of chamber **105** is analogous to an EM waveguide where the signal strength is maximized by locating the port(s) at the node(s) and antinode(s) of the waveguide. The signal received at the location of the valve is then demodulated by the periodical operation of the valve(s), which is analogous to the synchronous local oscillator of an AM receiver, and the nonlinear characteristics of Z_{VALVE}, which is analogous to the mixer of an AM receiver and generate the output, P**707**R/P**707**R, by dividing P**112**/P**114** by the impendence $Z_{VALVE}(t)$ of its corresponding valve.

As an example, supposed that the plots Z**101**, P**112**, Z**103** and P**114** are sinusoidal for simplicity, i.e., by virtue of interleaved driving signal S**101**, S**103** we have Z**101**$\propto\sin(\omega t)$, Z**103**$\propto-\sin(\omega t)$; and in the example illustrated in FIG. **1**, by virtue of n=1 standing wave, there will be a phase inversion between P**112** and P**114** and therefore we can express these two local pressure as P**112**$\propto S_{IN}\cdot\sin(\omega t)$, P**114**$\propto-S_{IN}\cdot\sin(\omega t)$, where the negative sign "–" represent the 180° phase difference, and $\omega=2\pi f_{CY}$. Assuming $Z_{VALVE}\propto 1/($Z**101**$-Z_{O/C})$ when Z**101**$>Z_{O/C}$ and $Z_{VALVE}=\infty$ otherwise, then P**707**L may be expressed as P**707**L$\propto S_{IN}\cdot\sin^2(\omega t)$ when Z**101**$>Z_{O/C}$ and P**707**L=0 otherwise. Likewise, P**707**R may be expressed as P**707**R$\propto S_{IN}\cdot\sin^2(\omega t)$ when Z**103**$>Z_{O/C}$ and P**707**R=0 otherwise. The quantity P**890**, being P**707**L+P**707**R, representing an acoustic sound produced by the device **890**. After substituting P**707**L and P**707**R we get P**890**=P**707**L+P**707**R$\propto S_{IN}\cdot\sin^2(\omega t)$ for all time in which the device **890** operates.

Note that, when a DSB-SC AM radio waveform, which has a mathematical expression of $S_{IN}\cdot\sin(\omega t)$, is demodulated by a carrier signal $\sin(\omega t)$, generated by a synchronous local oscillator, with a multiplier, the result can be expressed as $S_{IN}\cdot\sin(\omega t)\cdot\sin(\omega t)=S_{IN}\cdot\sin^2(\omega t)$, which is exactly the same mathematical expression for P**890** derived in the paragraph above.

As known by person having ordinary skill in the art, after multiplying the AM modulated signal/waveform $S_{IN}\cdot\sin(\omega t)$ by the demodulation signal $\sin(\omega t)$, ⅔ of the energy of the resulting signal (i.e., $S_{IN}\cdot\sin^2(\omega t)$) is in the baseband and ⅓ of the energy of the resulting signal is on a frequency band centered at twice of the carrier frequency, i.e., $2\cdot\omega$ or $2\cdot f_{CY}$. Illustratively, supposed that P**890**$\propto S_{IN}\cdot\sin^2(\omega t)=S_{IN}\cdot(\frac{1}{2}-\frac{1}{2}\cos(2\omega t))$ (eq. 3). The 1st term in eq. 3, $\frac{1}{2}\cdot S_{IN}$, represents demodulated component on the baseband; while the 2nd term in eq. 3, $\frac{1}{2}\cdot S_{IN}\cdot\cos(2\omega t)$, represents component in the ultrasonic band. As can be seen from eq. 3, a first energy of the 1st term within the baseband is twice of a second energy of the 2nd term. The baseband herein refers to a frequency band of the input audio signal S_{IN}, and this baseband covers/overlaps with human audible frequency band.

In FIG. **1** (or FIG. **6**), material of oxide substrate underneath the valves **101**, **103**, the membrane portions **102***a*, **102***b* may be removed by photo lithography process/processes, and supports **110** and walls **111** may be formed. According to patterns of very fine lines, Si or POLY layer(s) may be etched to form openings/slits. Such slits create free moving ends on the valve **101**/**103** (e.g., these slits may form the opening **112**/**114** when the displacement of the free-moving ends of the valves exceed $Z_{O/C}$). Alternatively, slits can increase the compliance of the membrane portion **102***a*/**102***b* (e.g., by forming slits **113***a*, **113***b* on the membrane portions **102***a*, **102***b*).

FIG. **5** is a schematic diagram illustrating a top view of the air-pulse generating device **890** shown in FIG. **1**. The air-pulse generating device **890** may (optionally) include cross linked beams **871**, **872** to break down the (long) valves **101**, **103** or the (long) membrane portions **102***a*, **102***b* into shorter pieces and to reinforce the supports **110** and **891**. The air-pulse generating device **890** may (optionally) have slot(s) **873**, which may be created by widening one slit on a membrane portion to function as an airflow pathway to allow pressure to be release. Herein, a slit generally has a width corresponding to the etching resolution of a MEMS fabrication process, such as a width of 0.5~1.8 μM over 3~7 μM-thick Si membrane; a slot refers to a line geometry width that is not restricted to the limits of the MEMS fabrication process.

Higher Harmonics

Higher harmonic resonance may occur in an air-pulse generating device. For example, FIG. **7** is a schematic diagram of a cross sectional view of an air-pulse generating device **850** according to an embodiment of the present application. In the air-pulse generating device **850**, the width W_{105} between the side walls **804**L and **804**R may be one wavelength (λ) corresponding to the operating frequency f_{CY} to achieve 2nd mode (or n=2 mode) resonance. In 2nd mode resonance, 2 air-motion antinodes exist within the chamber **105** (for instance, at/near a quarter (¼) of the width W_{105} from either side wall **804**L or side wall **804**R); 3 air-motion nodes locate at the center of the chamber **105** and near the side walls **804**L, **804**R; 2 air-pressure nodes exist within the chamber **105** (for instance, at/near a quarter (¼) of the width W_{105} from either side wall **804**L or **804**R); 3 air-pressure antinodes locate at the center of the chamber **105** and the side walls **804**L, **804**R. The curve W**102** schematically representing pressure distribution within the chamber **105** over time may be caused by the movement of membrane portions **102***c* and **102***d* of the air-pulse generating device **830** and symmetrical relative to a center line **703**. As illustrated by W**102** in FIG. **7**, when a n=2 mode standing wave is formed within chamber **105** of device **850**, by driving membranes **102***e* and **102***f* in synchronous with the one common waveform such as S**102***a*", air-pressure waveform near sidewall **804**L and **804**R will be in-phase with each other and a phase inverted air-pressure waveform of similar amplitude will be produced at the center of chamber **105**. The valve opening **112** of the air-pulse generating device **850** may therefore be located at/near a center location between the side walls **804**L and **804**R, since an air-pressure antinode is located at the center of the chamber **105** (or the width W_{105}). In other words, for higher harmonic resonance (namely, n≥2), in addition next to side walls **804**L and **804**R, opening(s) of air-pulse generating device(s) may also be at/near any air-pressure antinode between the two side walls causing resonance.

The same description of the last paragraph is also applicable to device **830** of FIG. **6**.

In the air-pulse generating device, such as device **830** of FIG. **6**, device **850** of FIG. **7** or device **890** of FIG. **1**, the demodulation operation of the valves **101** and **103** will produce pulses of airflow which will accumulate across consecutive pulses, causing a long-term net air mass change inside chamber **105** and increase/decrease the pressure P**0** within the chamber **105**. Since such back pressure will cause the output SPL to drop, it is therefore suggested to release such pressure.

In the case of air-pulse generating device **830** of FIG. **6**, the slit opening **113***a**/**113***b** may be designed to be close to the air-pressure node located at $W_{105}/4$ away from the side wall **804**L/**804**R. Due to acoustic filter effect of air-pressure node of n=2 standing wave, as illustrated by the waveform W**102** crossing P**0**, enlarged slit **113***a**/**113***b** will have minimum impact on the operation of device **830** while releasing the pressure build up due to the demodulation operation of the valves **101** and **103**, illustrated by valve opening **112**.

In the case of air-pulse generating device **850** in FIG. **7**, which also operate with at frequency f_{CY} corresponding to n=2 mode resonance across the width of the chamber W_{105}, the membranes **102***e* and **102***f* each comprise of 1 single piece of thin flap, attached to their respective support **110**. As opposed to the situation in the device **830**, where the membranes **102***c*, **102***d* are each made of two sub-portions, separated by slits **113***a* and **113***b* respectively, in device **850**, since slits **112** and **114**, created to allow free movement of membranes **102***e* and **102***f*, are located at the air-pressure anti-nodes within chamber **105** of device **850**, the width of these slits needs to be minimized to suppress the leakage of air-pressure. Therefore, one or multiple vent(s) **713**T can be created on the top cap, at the location(s) of the air-pressure node(s), for example, at a distance of $W_{105}/4$ away from side walls **804**L and **804**R. Although theoretically speaking, one such vent may suffice for the back-pressure release purpose, however, for the consideration of optimal balancing of air pressure within chamber **105**, it is generally a good practice to have a pair of vents **713**T, positioned in a center-mirroring fashion, as illustrated in FIG. **7**.

In the case of air-pulse generating device **890** in FIG. **1**, pressure pulses of the acoustic sound (e.g., the acoustic sound P**890**) out of the valves **112** and **113** have the same polarity, which combine together to increase/decrease the pressure P**0** within the chamber **105**. Therefore, vent openings **713**T on the top plates, located at or near the air-pressure node, as indicated by alignment to the position where air-pressure profile W**102** crosses P**0**, is created to allow airflow to pass through, releasing the pressure build up due to the demodulation operation of the valves **101** and **103**.

The length and width of the vent opening(s) **713**T may be adjusted to form a suitable acoustic low pass filter (LPF) with the volume of the chamber **105**. The location of the vent opening(s) **713**T may be at air-pressure node(s), relative to operating frequency f_{CY}, where the amplitude of frequency components corresponding to the standing wave is nearly zero. As a result, an acoustic notch filter is formed and the pressure corresponding to the amplitude modulated standing wave may be suppressed near/at the vent opening(s) **713**T inside the chamber **105**, and only the pressure change due to the demodulation operation may be present near/at the vent opening(s) **713**T. For devices operated in the 2nd mode resonance (e.g., the device **850**), the vent opening **713**T of the air-pulse may be positioned approximately at a quarter of the width W_{105} ($W_{105}/4$) from either of the side walls **804**R and **804**L, which is different from the device operating in the 1st mode resonance (e.g., the device **890**), where the vent opening **713**T (of the air-pulse generating device **890**) may be near the midpoint between the two side walls **804**R and **804**L.

The structure of an air-pulse generating device **850** may be altered according to different design consideration. For example, the membrane **102***e*/**102***f* may have two membrane sub-portions, or 2-pieces, like membrane **102***a*/**102***b* or **102***c*/**102***d* does, but is not limited thereto. Note that the maximum Z-direction displacement of 1-piece membrane construct, such as **102***e*/**102***f* in FIG. **6**, needs to be significantly smaller than the thickness (a Z-direction value) of **102***e*/**102***f* to avoid leakage of the air pressure inside chamber **105**. In comparison, in the 2-piece per membrane construct, since the two sub-portions always moves in tandem, such Z-direction membrane displacement limitation does not exist, meaning larger displacement may be possible and therefore lead to improved unit-device-area effectiveness (SPL per meter).

Furthermore, the valve portions **101** and **103** illustrated in FIG. **7** may be considered as a virtual valve. In other words, a slit formed between the valve portions **101** and **103**, may become a temporarily formed/opened valve opening (**112'**) when the valve portions **101** and **103** is sufficiently actuated. In addition, the temporarily formed/opened valve opening is formed periodically. When the opening is opened, the chamber and ambient environment are connected via the opening (**112'**). When the opening is not opened, air flowing through the slit is negligible or less than a threshold. Details of virtual valve (temporarily formed opening) may be referred to U.S. Pat. No. 11,043,197, which is not narrated herein for brevity.

In addition, similar to the device **890** shown in FIG. **1**, pressure gradients are also generated in the device **850** via membrane movement and the nature of standing wave. Different from the device **890**, the membrane portions **102***e* and **102***f* are actuated to move in an in-phase fashion, referring that at a certain time, both the membrane portions

102*e* and **102***f* are actuated to move upward (or downward). In this case, pressure gradients are also established by utilizing the nature of n=2 standing wave as well. Similar to description of FIG. **1**, in FIG. **7**, dashed lines of the curves U**102** and W**102** are corresponding to the time t_0 and solid lines of the curves U**102** and W**102** are corresponding to the time t_1. At the time t_0, the membrane portions **102***e* and **102***f* are actuated to move upward (in positive Z direction), pressure gradients are generated in inward direction (in X direction), as illustrated by the slope of dashed line of W**102**. At the time t_1, the membrane portions **102***e* and **102***f* are actuated to move downward (in negative Z direction), pressure gradients are generated in outward direction (in X direction), as illustrated by the slope of solid line of W**102**. Similarly, the membrane movement directions are substantially perpendicular to the pressure gradient directions.

Air Movement or Fan Application

The structure/mechanism of device **890**/**830**/**850** may be reproduced/adapted for an air movement or fan application. Different from an acoustic wave traveling at the speed of sound, C, an air movement is the airflow related to the kinetic movement of air particles, as that of wind, and is produced by the displacement of membrane portion(s), corresponding to membrane portions **102***a*-**102***d*/**102** of the air-pulse generating device **890**/**830**/**850**. In an air movement or fan application/mode of these devices, air particles within the device may be described mainly according to fluid dynamics or aerodynamics; in contrast, in an air-pulse (APPS) generating application/mode of these devices, the behavior of air within the device may be described mainly according to acoustics.

For air movement or fan application, valve opening(s), such as the openings **112** and **114** illustrated in device **890**/**830**/**850**, may be formed spatially on a location, and temporarily in time, such that the air motion is maximized, wherein the peak of the air motion may be in terms of the velocity of the air moved or in terms of the volume of air moved.

Driving signal(s) of the device for the air-flow generation or fan application differs from that of the APPS application. For example, in air movement or fan application, device **890** may actuate its two membranes (**102***a* and **102***b*) to move synchronously, by applying the same driving signal to both membrane **102***a* and **102***b*, to create a pressure difference between the volume inside chamber **105** and the ambient outside of device **890**. In comparison, in APPS application, device **890** would actuate its two membranes (**102***a* and **102***b*) to move symmetrically, in opposite direction (along Z axis), by applying two interleaved (such as S**102***a*, S**102***b*) or polarity inverted (such as S**102***a*", −S**102***a*") driving signals to membrane **102***a* and **102***b*, to create pressure gradient (vector **116**) within chamber **105**, atop the two membranes.

A key difference between these two modes of operation lies in the different relationship between the chamber dimension and the operating frequency of device. As described in association with device **890**/**830**/**850** for APPS application, the operating frequency may be selected to produce a standing wave of mode n within chamber. In other words, the operating frequency f_{CY} is related to chamber width W**105** by equation $W_{105}=n/2\cdot\lambda_{CY}$, where $\lambda_{CY}=C/f_{CY}$ is the characteristic length or wavelength of f_{CY} and n is a small positive integer such as 1-3. On the other hand, for the air movement or fan application of device **890**/**830**/**850**, the conversion rate of membrane movement into airflow generally increases as the ratio $\lambda_{CY}/W_{chamber}$ increases, where $W_{chamber}$ is the chamber width of the device, corresponding to width of the chamber **105**, W_{105}, of the air-pulse generating device **890**/**830**/**850**. In other words, the conversion rate of membrane movement into airflow typically increases when the pressure within the chamber of the air-flow generating device for the air movement or fan application (corresponding to the chamber **105** of the air-pulse generating device **890**/**830**/**850**) becomes more uniform, exactly opposite to the desire to maximize the pressure gradient (or the nonuniformity of the pressure within chamber **105**) of the air-pulse generating device **890**/**830**/**850**.

For example, in the air-pulse generating device **890**, $W_{105}=\lambda_{CY}=3.6$ mm at operating frequency of 96 KHz since the resonance frequency f of a cantilever beam may be related to its length L by $f\propto 1/L^3$. On the other hand, by lowing the operating frequency of the air-pulse generating device for the air movement or fan application from 96 KHz down to 24 KHz and lowering the resonance frequency of both the membrane portion(s) and the valve portion(s) of the air-pulse generating device for the air movement or fan application also to 24 KHz, the width of the membrane portion may increase from 0.94 mm to 1.44 mm, the width of the valve portion may increase from 0.46 to 0.73 mm, and the resulting width of the chamber may be $2\times(0.1+0.73+0.2)+1.44=3.5$ mm, which is much shorter than the wavelength of 14.6 mm at frequency of 24 KHz, indicating a higher conversion rate of membrane movement into airflow. Therefore, despite almost identical cross-section view, an air-pulse generating device for the air movement or fan application with the resonance frequency of 24 KHz for both the membrane portion(s) and the valve portion(s) and driving both membrane portions of the air-pulse generating device for the air movement or fan application with the same waveform at 24 KHz may be suitable for air moving applications while the air-pulse generating device **890**, where the membrane portion **102***a* and **102***b* are driven by interleaved waveforms S**102***a*', S**102** *b*' or symmetrical waveforms S**102***a*", −S**102***a*" to produce near-0 net air movement over each operating cycle T_{CY}, may be optimized for sound production applications and not suitable as an air movement apparatus.

In a word, while symmetrical membrane displacements of the membrane portion **102***a*/**102***b* or **102***c*/**102***d* of device **890** may be used to maximize the in-chamber pressure gradient for APPS applications, synchronous/identical membrane displacement (by driving membrane portions with signal of the same polarity) may be adopted to maximize the conversion rate of membrane movement to airflow. In another perspective, for APPS applications, the chamber width (in X direction) W_{105} may be equal or close to $n/2\times\lambda_{CY}$ (where n is a small positive integer) in order to maximize its acoustic output by leveraging chamber resonance (i.e. standing wave); on the other hand, for air movement applications, the chamber width (in X direction) of an air-pulse generating device for the air movement or fan application may be much smaller than $\lambda_{CY}/2$ to maximize the conversion rate of membrane movement to airflow.

Different structural embodiments (air-pulse generating) device are described in the following paragraph. For example, FIG. **8** is a schematic diagram of a cross sectional view of an air-pulse generating device **880** according to an embodiment of the present application. The membrane structure **12** of the air-pulse generating device **880** includes one membrane portion, which is divided into membrane subparts **102***e*', **102***f*' and **102***g*. The membrane subparts **102***e*' and **102***g* may be differentiated according to slits **113***e* and **113***f* on the membrane portion. The membrane structure **12** of the air-pulse generating device **880** with the membrane subparts **102***e*' and **102***g* may serve/function as the membrane portions **102***a* and **102***b* of the air-pulse generating device **890** (or the membrane portions **102***c* and **102***d* of the air-pulse generating device **830**).

For APPS applications, the membrane subparts **102***e*' and **102***g* may be driven by a pair of membrane driving signals similar to the membrane driving signal pair (**S102***a*, **S102***b*)/(**S102***a*', **S102***b*')/(**S102***a*", **S102***b*"), such that the membrane subparts **102***e*' and **102***g* may move almost oppositely to have symmetrical membrane displacements. Similar to the membrane portion **102***a* bending downwards and the membrane portion **102***b* bending upwards, the membrane subparts **102***e*' and **102***f*' may be curved concavely to bend downwards while the membrane subparts **102***f*' and **102***g* may be curved convexly to bend upwards, and vice versa.

FIG. **9** is a schematic diagram of a cross sectional view of an air-pulse generating device **800** according to an embodiment of the present application. The membrane structure **12** of the air-pulse generating device **800** includes membrane portions **102***g* and **102***h*, which are anchored on the support **110** at the center of the air-pulse generating device **800**. The slits/tips of the membrane portions **102***g* and **102***h* are located close to the side wall **804**L and **804**R.

The valves **101** and **103** of the air-pulse generating device **890**/**830**/**850**/**880** are absent from the air-pulse generating device **800**. When the membrane portions **102***g* and **102***h* are driven by the pair of the membrane driving signals (**S102***a*, **S102***b*)/(**S102***a*', **S102***b*')/(**S102***a*", **S102***b*"), the membrane portions **102***g* and **102***h* may provide the pressure regulation function of the valves **101**, **103** of the air-pulse generating device **890** and the pressure generation function of the membrane portions **102***a*, **102***b* of the air-pulse generating device **890** by utilizing the slits between the membrane portions **102***g*, **102***h* and the walls **111** to perform the AM ultrasonic carrier rectification function of the openings **112**, **114** of the valves **101**, **103** of the air-pulse generating device **890**.

As a result, the membrane portion **102***g* may vibrate to form opening **112***g* functioned as the opening **112** of the valve **101** and meanwhile create the maximum/minimum change in pressure (e.g., the first peak pressure pk_1). The membrane portion **102***h* may vibrate to form the opening **114***h* functioned as the opening **114** of the valve **103** and meanwhile create the maximum/minimum change in pressure (e.g., the second peak pressure pk_2).

The air pressure waveform P**707**L may be expressed as $P707L \propto (S_{IN} \cdot \sin(\omega \cdot t) + Z_{0AC})^2$ when $Z102a > Z_{O/C}$ and P**707**L=0 otherwise. The air pressure waveform P**707**R may be expressed as $P707R \propto (S_{IN} \cdot \sin(-\omega \cdot t) + Z_{0AC})^2$ when $Z102b > Z_{O/C}$ and P**707**R=0 otherwise. Herein, waveforms Z**102***a*, Z**102***b* represent displacement of the membrane portions **102***g*, **102***h* respectively; waveform P**707**L, P**707**R represent air pressure at the ports **707**L, **707**R (out of the chamber **105**) respectively.

A negative bias voltage may be applied to bottom electrode(s) of actuator(s) of the membrane portion **102***g*/**102***h*, such that the position of (the tip of) the membrane portion **102***g*/**102***h* in the Z direction is lifted to be equal to or slightly above the displacement level $Z_{O/C}$ when the input AC voltage is 0V. In other words, Z_{0AC} may be positive. If the position of (the tip of) the membrane portion **102***g*/**102***h* in the Z direction is below the displacement level $Z_{O/C}$ when the input AC voltage is 0V, Z_{0AC} may be negative, and a clipping phenomenon similar to class-B amplifiers may occur to low level input signal(s). In the clipping phenomenon, the membrane portion **102***g*/**102***h* may not be fully opened.

When Z_{0AC} is a positive number, an aggregated on-axis output acoustic pressure of the air-pulse generating device **800** (namely, P**800**=P**707**R+P**707**L) may be expressed as:

$$P800 \propto (S_{IN} \cdot \sin(\omega \cdot t) + Z_{0AC})^2 + (S_{IN} \cdot \sin(-\omega \cdot t) + Z_{0AC})^2 = S_{IN}{}^2 \cdot (1 - \cos^2(2\omega \cdot t) + 2 \cdot Z_{0AC}{}^2 \text{ when } |S_{IN} \cdot \sin(\omega \neq t)| < Z_{0AC} \quad \text{(eq. 5a)},$$

$$P800 \propto (S_{IN} \cdot \sin(\omega \cdot t) + Z_{0AC})^2 \approx \tfrac{1}{2} \cdot S_{IN}{}^2 \cdot (1 - \cos^2(2\omega \cdot t) + 2 \cdot S_{IN} \cdot \sin(\omega \cdot t) \cdot Z_{0AC} \text{ when } |S_{IN} \cdot \sin(\omega \cdot t)| >> Z_{0AC} \quad \text{(eq. 5b), and}$$

$$P800a \propto (S_{IN} \cdot \sin(\omega \cdot t)^2 \approx \tfrac{1}{2} S_{IN}{}^2 \cdot (1 - \cos^2(2\omega \cdot t)) \text{ when } Z_{0AC} \rightarrow 0+ \quad \text{(eq. 5c).}$$

Z_{0AC} is the membrane displacement relative to the displacement level $Z_{O/C}$ when the input AC voltage is 0V.

In an embodiment, Z_{0AC} may be set to a small positive value to reduce the second term $2 \cdot Z_{0AC}{}^2$ in eq. 5a and the inaudible second term $2 \cdot S_{IN} \cdot \sin(\omega \cdot t) \cdot Z_{0AC}$ in eq. 5b. For example, Z_{0AC} may range between 1%-10% of the maximum membrane displacement.

In an embodiment, to compensate the nonlinearity of $S_{IN}{}^2$ in eq. 5a to eq. 5c, linearity compensation may be performed by a DSP function block embedded within a host processor.

By setting Z_{0AC} to a small positive value, the membrane portion **102***g*/**102***h* may be slightly open when the input AC voltage is 0V. Given the symmetricity of the membrane driving signal (**S102***a*, **S102***b*)/(**S102***a*', **S102***b*')/(**S102***a*", **S102***b*"), at least one of the openings **112***g*, **114***h* may be slightly open/formed at any time. Therefore, the pressure change inside the chamber **105** due to the rectification effect of the openings **112***g*, **114***h* may be balanced, and the vent opening(s) **713**T or the wider slit openings **113***a**/**113***b** may be absent from the air-pulse generating device **800**.

In the air-pulse generating device **800**, whether resonance occurs in the chamber **105** or not, the effect of full-wave rectification and synchronous demodulation may be produced by the air-pulse generating device **800**. Even without any standing wave to create the maximum acoustic pressure at or near the side walls **804**L and **804**R, such maximum acoustic pressure may occur simply as a result of the physical location of the openings **112***g*, **114***h* of the membrane portions **102***g*, **102***h* and the symmetrical membrane driving signals (**S102***a*, **S102***b*)/(**S102***a*', **S102***b*')/(**S102***a*", **S102***b*"), which drive the actuators of the membrane portions **102***g*, **102***h* to cause the maximum displacements near the side walls **804**L and **804**R. For example, the membrane portion **102***g* may be actuated to compress the first part/volume **105***a* (on the top of the membrane portion **102***g*) within the chamber **105** to maximum the local pressure. The membrane portions **102***h* may be actuated to expand the second part/volume **105***b* (on the top of the membrane portion **102***h*) within the chamber **105** to minimum the local pressure. The pressure profile over time within the part/volumes **105***a* and **105***b* may be identical to that of a standing wave in the 1st mode resonance. In other words, the air-pulse generating device **800** may achieve full-wave rectification and synchronous demodulation without the resonance of the chamber **105**, thereby increasing flexibility in the design of an air-pulse generating device.

In the air-pulse generating device **800**, if resonance occurs, the output of the air-pulse generating device **800** may benefit from the standing wave of such resonance. For example, when the width W_{105} of the chamber **105** of the air-pulse generating device **800** equals half of the wavelength (λ/2) corresponding to the operating frequency f_{CY}, a pressure profile similar to that of a standing wave may be established by the movements of the membrane portions

102g and **102**h and therefore enhance the output caused by the standing wave having already established within the chamber **105**.

Enclosure-Less

Since the air pulse generating device **890**/**850**/**830** do not generate a pair of out-of-phase baseband radiations, as produced by a conventional speaker (namely, a front radiation and a phase-inverted back radiation), the air-pulse generating device **890**/**850**/**830** do not require any back enclosure (whose purpose is to contain or transform to the back radiation and prevent the phase inverted back radiation from cancelling out the front radiation) as a conventional speaker does. Therefore, the air pulse generating device **890**/**850**/**830**, which produces sound, can be enclosure-less.

In the case of device **890**, by utilizing the 1st mode resonance of the chamber **105** and the interleaved timing of valve opening, the air-pulse generating device **890** produces two radiations that are in-phase instead of 180° out of phase. By proper timing alignment between open timing of valve **101**/**103** (denoted by Z**101**/Z**103** in FIG. **2**) and pressure wave P**112**/P**114**, the phase of acoustic energy is properly phase aligned and the ultrasonic radiation is transformed to double the baseband output SPL, increases the utilization rate of the total acoustic energy, achieve effective demodulation of ultrasonic AM signal while obliterate the need for an enclosure.

Acoustic Filter

An acoustic filter may be added in front of the air-pulse generating device. For example, FIG. **10** is a schematic diagram of the air-pulse generating device **890** disposed within a construct A**00** according to an embodiment of the present application. FIG. **11** is a schematic diagram of the air-pulse generating device **890** disposed within a construct A**30** according to an embodiment of the present application. The acoustic air pressure measured at the ports **707**L and **707**R of the air-pulse generating device **890** may include not only the demodulated AM ultrasonic waves P**707**L and P**707**R but also ultrasonic waves generated by the motion of the valves **101** and **103**. The symmetrical movements of the valves **101** and **103** may be characterized as a dipole. The superposition of the ultrasonic waves generated by the motion of the valves **101** and **103** may peak along the plane of the valves **101** and **103** and become null on the center plane between the side walls **804**L and **804**R. The construct A**00**/A**30** may be configured to minimize the ultrasonic waves generated by the motion of the valves **101** and **103** and thus served as an acoustic filter.

In FIG. **10**, the construct A**00** may include a funnel structure A**05** configured to filter out the ultrasonic waves generated by the motion of the valves **101**/**103**. The funnel structure A**05** may have a wide opening on the inside of the construct A**00**, sloping sides, and a narrow tube near the outside of the construct A**00**. The wide opening of the funnel structure A**05** may be smaller than the width W_{105} of the chamber **105**. The funnel structure A**05** may merge the output from the ports **707**L and **707**R, causing the ultrasonic waves produced by the symmetrical movement of the valves **101** and **103** to annihilate each other and leaving behind the wave P**890**, which is the sum/superposition of the waves P**770**L and P**770**R.

In FIG. **11**, the construct A**30** may include an external chamber A**06** and a port A**07** serving as the output port for the construct A**30**. The width Wa**06** between side walls A**06**T, A**06**B of the external chamber A**06** may equal the width W_{105} of the chamber **105** (e.g., half of λ_{CY}), such that a standing wave may occur at both the frequency f_{CY} (for 1st mode resonance) and the frequency $2 \cdot f_{CY}$ (for 2nd mode resonance). The width Wa**07** of the port A**07** may be smaller than the width W_{105} of the chamber **105**. The width Wa**07** of the port A**07** may be equal to half of the width W_{105} of the chamber **105** or a quarter of λ_{CY}.

The construct A**30** is configured to filter out the ultrasonic waves generated by the motion of the valves **101**/**103**. For the ultrasonic waves generated by the symmetrical movement of the valves **101** and **103**, which has the frequency f_{CY}, the acoustic energy may reside in the 1st mode resonance of the external chamber A**06** with the air-pressure node at/near the midpoint between the side walls A**06**T and A**06**B, and the pressure of the standing wave may be merged to zero over the width Wa**07** of the port A**07**. For the acoustic wave P**890**, which has the pulse rate $2 \cdot f_{CY}$, the acoustic energy may reside in the 2nd mode of the external chamber A**06** with an air-pressure antinode at/near the midpoint between the side walls A**06**T and A**06**B, which is also the center of the port A**07**, and the maximum output pressure may be produced when the pressure of the standing wave is integrated over the width Wa**07** of the port A**07**. By utilizing two different resonance modes, the external chamber A**06** may remove the ultrasonic spectral component at the frequency f_{CY} by the 1st mode resonance and pass ultrasonic spectral component at the frequency $2 \cdot f_{CY}$ (namely, the wave P**890**) by the 2nd mode resonance.

In FIG. **11**, the construct A**30** may include a film A**08**, which may be made of aquaphobia material. The film A**08** may be place within the port A**07** to function both as a protective means (to prevent dust, vapors and moisture from entering) and as acoustic resistance (to attenuate the remaining ultrasonic spectral component at the frequency $2 \cdot f_{CY}$ by forming a low-pass filter with the volume of the external chamber A**06**).

FIG. **12** is a schematic diagram of a mobile device A**60** according to an embodiment of the present application. Two air-pulse generating devices A**02** and A**03**, each of which may be any of the air-pulse generating devices **890**/**850**/**830**, are mounted onto an edge A**01** of the mobile device A**60** such as a smartphone or notepad. The ports **707**L and **707**R of the air-pulse generating devices A**02**, A**04** may face outward, and the ultrasonic acoustic wave produce by the air-pulse generating devices A**02**, A**03** may pass through orifice-arrays A**04**, A**05**. The mobile device A**60** may utilize the structure of the construct A**00** or A**30** to remove the ultrasonic spectral component at the frequency f_{CY} produced by the motion of the valves **101** and **103** while allowing the wave P**890** at the frequency $2 \cdot f_{CY}$ to pass through. The film A**08** of the construct A**30** may reduce the remaining ultrasonic spectral component around the frequency $2 \cdot f_{CY}$ further.

FIG. **13** is a schematic diagram of a cross sectional view of an air-pulse generating device **300** according to an embodiment of the present application. Similar to the air-pulse generating device **890**, when a standing wave is formed with the chamber **105** of the air-pulse generating device **300**, the movements of the membrane portions **102**c and **102**d of the air-pulse generating device **300** is symmetrical and may produce near 0 net air movement. Because of the near 0 net air movement over each operating cycle T_{CY}, most of the energy exerted by the membrane portions **102**c/**102**d becomes acoustic energy (in the form of air pressure gradient or a standing wave) and near zero energy becomes kinetic energy (in the form of air mass movement, i.e., wind).

FIG. **14** is a schematic diagram of a cross sectional view of an air-moving device **100** for moving air volume from one port of the device to another port, according to an embodiment of the present application.

Contrary to the air-pulse generating device **850/890**, the vibration frequency of the membrane **102** of the air-flow generating device **100** will produce a wavelength λ much greater than the width of chamber **105**, and the pressure inside the chamber **105** may be considered to be uniform. The interleaved valve driving signals S**101**, S**103** may be configured to open the valve portions **101**, **103** in a time interleaved manner, or 180° out of phase, and produce air movement either from port **107** to port **108**, or from port **108** to port **107**. For example, if valve **101/103** is open and valve **103/101** is closed when membrane **102** moves in a positive Z direction (+Z direction) to compress the volume within chamber **105**, the air will flow out of chamber **105** via port **107/108**. Conversely, if valve **101/103** is opened and valve **103/101** is closed when membrane **102** moves in a negative Z direction (−Z direction) to expand the volume of chamber **105**, the air will flow into chamber **105** via port **107/108**.

The cap **104** of the air-moving device **100** may function as a heat dissipation plate/pad, making physical contact with heat generating components such as notebook central processing unit (CPU) or smartphone application processor(s) (AP), but is not limited thereto. The cap **104** may be made of heat conducting material such as aluminum or copper. To improve the heat transfer efficiency, fine fins (not shown) may be formed on the surface of the cap **104** inside the chamber **105**, but not limited thereto.

Notably, in the air-pulse generating device **850/890**, the cap **104** of the air device **100/300** is replaced by the top plate **804**T and the spacers **804**L, **804**R which also serve as side walls. The top plate **804**T may be a printed circuit board (PCB) or a land grid array (LGA) substrate and includes metal traces, vias and contact pads which may be otherwise presented on the substrate **109** or the plate **115**. The thicknesses may be 0.2~0.3 mm for the top plate **804**T, 0.05~0.15 mm for the side walls **804**L/**804**R and 0.25~0.35 mm for the wall **111**. The total thickness of an air-pulse generating device may be 0.6~0.8 mm, but not limited thereto.

Furthermore, pulse interleaving concept disclosed in U.S. Pat. No. 10,536,770 may be also applied in the present application. In other words, while producing ultrasonic acoustic pulses for APPS, in order to improve the quality of sound, in an embodiment, multiple air-pulse generating devices (e.g., multiple air-pulse generating devices **100**) may be cascaded together to form one single air-pulse generating device. The driving signals for the air-pulse generating devices **100** (e.g., the membrane driving signal S**102***a*/S**102***b*/S**102** or the valve driving signal S**101**/S**103**) may be interleaved to form an interleaved group and raise the effective air pulse rate to a twice higher frequency as a result, away from human audible band. For example, pulses of the membrane driving signal of one air-pulse generating device **100** may be interleaved with pulses of the membrane driving signal of another air-pulse generating device **100**, such that the aggregated air pulses of one air-pulse generating device **100** may be interleaved with the aggregated air pulses of another air-pulse generating device **100** to increase the effective air pulse rate. Alternatively, each pulse of the membrane driving signal of one air-pulse generating device **100** may locate at/near a mid-point between two successive pulses of the membrane driving signal of the other air-pulse generating device **100**, such that each aggregated air pulse of one air-pulse generating device **100** locate at/near a mid-point between two successive aggregated air pulses of the other air-pulse generating device **100** to increase the effective air pulse rate. In an embodiment, two air-pulse generating devices **100**, each designed to operate at the operating frequency T_{CY} of 24 KHz, may be placed side-by-side or attached back-to-back and driven in interleaved manner, such that the effective air pulse rate becomes 48 KHz.

Illustratively, FIG. **15** is a schematic diagram of an air-pulse generating device **400** according to an embodiment of the present application. The air-pulse generating device **400** may be regarded as two air-pulse generating devices **100** and **100'** stacked back-to-back. In the air-pulse generating device **400**, two chambers **105** and **105'** of the two air-pulse generating devices **100** and **100'** are connected together via an opening **116** to form a chamber **106** of the air-pulse generating device **400**.

The air-pulse generating device **400** may comprise a first valve portion **101**, a second valve portion **103**, a third valve portion **101'**, and a fourth valve portion **103'**. A first anchor where the valve portion **101** is anchored on the wall **111** and a second anchor where the valve portion **103** is anchored on the wall **111** are aligned to the X direction; on the other hand, the first anchor and a third anchor where the valve portion **101'** is anchored on the wall **111** are aligned to the Z direction. The valve portions **101** and **103** (or the valve portions **101'** and **103'**) are symmetric with respect to the YZ plane; on the other hand, the (unactuated) valve portions **101** and **101'** (or the valve portions **103** and **103'**) are symmetric with respect to a second plane (e.g., the XY plane) nonparallel to the YZ plane when the valve driving signal S**101** (or S**103**) applied to the valve portions **101** and **101'** drops to zero. The valve portions **101** and **101'** (or the valve portion **103** and **103'**) are noncoplanar, while the (unactuated) valve portion **101** and **103** (or the valve portion **101'** and **103'**) may be coplanar when the valve driving signals S**101** and S**103** applied to the valve portions **101** and **103** drop to zero.

In an embodiment of APPS application, by interleaving the driving signals of the two air-pulse generating devices **100**, the displacement profile(s) of the membrane portion **102** (or the valve portions **101**, **103**) of the air-pulse generating device **400** may be mirror symmetric to the displacement profile(s) of membrane portion **102'** (or valve portions **101'**, **103'**) of the air-pulse generating device **400**. Alternatively, by interleaving or inverting the driving signals of the two air-pulse generating devices **100**, the displacement profile(s) of the membrane portion **102** (or the valve portions **101**, **103**) of the air-pulse generating device **400** may be the same as the displacement profile(s) of membrane portion **102'** (or valve portions **101'**, **103'**) of the air-pulse generating device **400**, such that (the direction and the magnitude of) the displacement of the membrane portion **102** may equal (the direction and the magnitude of) the displacement of the membrane portion **102'**, causing the pressure fluctuations in the chamber **106** to be cancelled. The membrane portion **102** may be parallel to (or be offset to match) the membrane portion **102'**.

In an embodiment of air moving application, the characteristic length λ_{CY} is generally much longer than the dimension of the air-pulse generating device **400**. Since the displacement of the membrane portion **102** may equal the displacement of the membrane portion **102'**, the air-pulse generating device **400** may include only one membrane portion, and one of the membrane portions **102**, **102'** may be removed, thereby reducing power consumption and improving operation efficiency.

Power Saving

In another perspective, the output of an air-pulse generating device is related to $A(t) \cdot p(t)$, where $A(t)$ is the area of the opening **112/114**, and $p(t)$ represents air pressure with the chamber **105**. In other words, the opening **112/114** of the valve **101/103** is directly related/proportional to the intensity of the output of an air-pulse generating device. Specifically, the maximum SPL output is a combination of the maximum of the air pressure p(t) within the chamber **105**, produced by membrane movement, and the maximum of the area A(t) of the opening **112**/**114**, produced by valve movement. By properly modulating/manipulating the area A(t), the operating power of an air-pulse generating device may be reduced.

The area A(t) may not change at a rate audible to human hearing, but may be adjusted by changing the valve driving voltage **S101**/**S103** slowly according to the volume or the envelope of the sound being produced. For example, the valve driving voltage **S101**/**S103** may be controlled by an envelope detection with an attack time of 50 milliseconds and a release time of 5 seconds. When the sound produced by the air-pulse generating device is consistently of low volume, the valve driving voltage **S101**/**S103** may be gradually lowered with the (long) release time of 5 seconds. When high sound pressure is to be generated, the valve driving voltage **S101**/**S103** may be boosted with the (short) 50-millisecond attack time.

To sum up, an air-pulse generating device of the present invention may produce an acoustic pressure (or air movement) by first vibrating its membrane structure, subsequently opening/closing its valve structure to filter/reshape the acoustic pressure (or air movement) in response to the occurrence of the maximum/minimum of acoustic pressure (or air velocity), and finally outputting a sound wave (or airflow) under a full-wave rectification effect. Synchronous demodulation may be performed by opening/closing its valve structure in a phase-locked and time-aligned manner relative to the occurrence of the maximum/minimum of acoustic pressure (or air velocity) and/or by opening/closing valve portions of the valve structure in a temporarily interleaved manner.

Those skilled in the art will readily observe that numerous modifications and alterations of the device and method may be made while retaining the teachings of the invention. Accordingly, the above disclosure should be construed as limited only by the metes and bounds of the appended claims.

What is claimed is:

1. An air-pulse generating device, comprising:

a membrane structure and a valve structure formed in a first layer;

a cover structure, wherein a chamber is formed between the membrane structure, the valve structure and the cover structure;

wherein an air wave vibrating at an operating frequency is formed within the chamber;

wherein the valve structure is configured to be actuated to perform an open-and-close movement to form at least one opening within the valve structure on the first layer, the at least one opening connects air inside the chamber with air outside the chamber;

wherein the open-and-close movement is synchronous with the operating frequency;

wherein the at least one opening is formed spatially within the valve structure on the first layer at a location where a peak of the air wave is achieved;

wherein the air-pulse generating device produces an acoustic sound according to an input audio signal;

wherein the air wave within the chamber, generated by the membrane structure, comprises an amplitude-modulated waveform corresponding to a carrier component with the operating frequency and a modulation component corresponding to the input audio signal.

2. The air-pulse generating device of claim **1**, wherein the peak of the air wave is in terms of air pressure.

3. The air-pulse generating device of claim **1**, wherein the peak of the air wave is in terms of air velocity.

4. The air-pulse generating device of claim **1**, wherein

a first opening is formed by a first side wall and a second opening is formed by a second side wall.

5. The air-pulse generating device of claim **1**, wherein the valve structure comprises a first valve portion and a second valve portion, configured to be actuated to form the at least one opening.

6. The air-pulse generating device of claim **1**, wherein

the valve structure forms the at least one opening at a center location between a first side wall and a second side wall substantially perpendicular to the membrane structure;

the cover structure comprises the first side wall and the second side wall.

7. An air-pulse generating device, comprising:

a membrane structure and a valve structure formed in a first layer;

a cover structure, wherein a chamber is formed between the membrane structure, the valve structure and the cover structure;

wherein an air wave vibrating at an operating frequency is formed within the chamber;

wherein the valve structure is configured to be actuated to perform an open-and-close movement to form at least one opening within the valve structure on the first layer, the at least one opening connects air inside the chamber with air outside the chamber;

wherein the open-and-close movement is synchronous with the operating frequency;

wherein the at least one opening is formed within the valve structure on the first layer within an interval during which a peak of the air wave is achieved;

wherein the air-pulse generating device produces an acoustic sound according to an input audio signal;

wherein the air wave within the chamber, generated by the membrane structure, comprises an amplitude-modulated waveform corresponding to a carrier component with the operating frequency and a modulation component corresponding to the input audio signal.

8. The air-pulse generating device of claim **7**, wherein the peak of the air wave is in terms of air pressure.

9. The air-pulse generating device of claim **7**, wherein

the valve structure forms a first opening during a first interval within an operating cycle;

the valve structure forms a second opening during a second interval within the operating cycle;

the operating cycle is corresponding to the operating frequency.

10. The air-pulse generating device of claim **9**, wherein

the operating cycle is a reciprocal of the operating frequency.

11. The air-pulse generating device of claim **9**, wherein the first interval and the second interval are non-overlapped.

12. The air-pulse generating device of claim **9**, wherein

the first opening is formed within the first interval during which a first peak of the air wave is achieved;

the second opening is formed within the second interval during which a second peak of the air wave is achieved.

13. The air-pulse generating device of claim **9**, wherein

the first opening is formed at a first location within the first interval, during which a first air pressure of the air wave corresponding to the first location within the chamber is greater than a certain pressure;

the second opening is formed at a second location within the second interval, during which a second air pressure of the air wave corresponding to the second location within the chamber is greater than the certain pressure.

14. The air-pulse generating device of claim **1**, wherein the membrane structure comprises a first membrane portion, the first membrane portion has a first slit, and the first slit is disposed at a location where an air-pressure node of air pressure of the air wave is achieved.

15. The air-pulse generating device of claim **14**, wherein the first slit is located a quarter of a width of the chamber from a first side wall or second side wall of the cover structure or at a center location between the first side wall and the second side wall.

16. The air-pulse generating device of claim **1**, wherein the cover structure comprises a top plate disposed parallel to the membrane structure, the top plate has a vent opening, and the vent opening is disposed near a location where an air-pressure node of air pressure of the air wave is achieved.

17. The air-pulse generating device of claim **16**, wherein the vent opening is located a quarter of a width of the chamber from a first side wall or second side wall of the cover structure or at a center location between the first side wall and the second side wall.

18. A sound producing method, applied in an air-pulse generating device comprising a membrane structure and a valve structure formed in a first layer, the method comprising:

forming an air wave within a chamber, wherein the air wave vibrates at an operating frequency, and the chamber is formed within the air-pulse generating device; and

forming at least one opening of the air-pulse generating device spatially within the valve structure on the first layer at a location where a peak of the air wave is achieved and at an opening frequency, wherein the at least one opening connects air inside the chamber with air outside the chamber;

producing, by the air-pulse generating device, an acoustic sound according to an input audio signal;

wherein the opening frequency is synchronous with the operating frequency;

wherein the air wave within the chamber, generated by the membrane structure, comprises an amplitude-modulated waveform corresponding to a carrier component with the operating frequency and a modulation component corresponding to the input audio signal.

19. A sound producing method, applied in an air-pulse generating device comprising a membrane structure and a valve structure formed in a first layer, the method comprising:

forming an air wave within a chamber, wherein the air wave vibrates at an operating frequency, and the chamber is formed within the air-pulse generating device; and

forming at least one opening within the valve structure on the first layer within an interval during which a peak of the air wave is achieved, on the air-pulse generating device, and at an opening frequency;

producing, by the air-pulse generating device, an acoustic sound according to an input audio signal;

wherein the at least one opening connects air inside the chamber with air outside the chamber;

wherein the opening frequency is synchronous with the operating frequency;

wherein the air wave within the chamber, generated by the membrane structure, comprises an amplitude-modulated waveform corresponding to a carrier component with the operating frequency and a modulation component corresponding to the input audio signal.

20. The sound producing method of claim **19**, wherein the step of forming the at least one opening comprises:

forming a first opening during a first interval within an operating cycle;

forming a second opening during a second interval within the operating cycle;

wherein the operating cycle is corresponding to the operating frequency.

21. The sound producing method of claim **20**, wherein the operating cycle is a reciprocal of the operating frequency.

22. The sound producing method of claim **20**, wherein the first interval and the second interval are non-overlapped.

23. The sound producing method of claim **20**, wherein the step of forming the at least one opening comprises:

forming the first opening within the first interval during which a first peak of the air wave is achieved;

forming the second opening within the second interval during which a second peak of the air wave is achieved.

24. The sound producing method of claim **20**, wherein the step of forming the at least one opening comprises:

forming the first opening at a first location within the first interval, during which a first air pressure of the air wave corresponding to the first location within the chamber is greater than a certain pressure;

forming the second opening at a second location within the second interval, during which a second air pressure of the air wave corresponding to the second location within the chamber is greater than the certain pressure.

* * * * *